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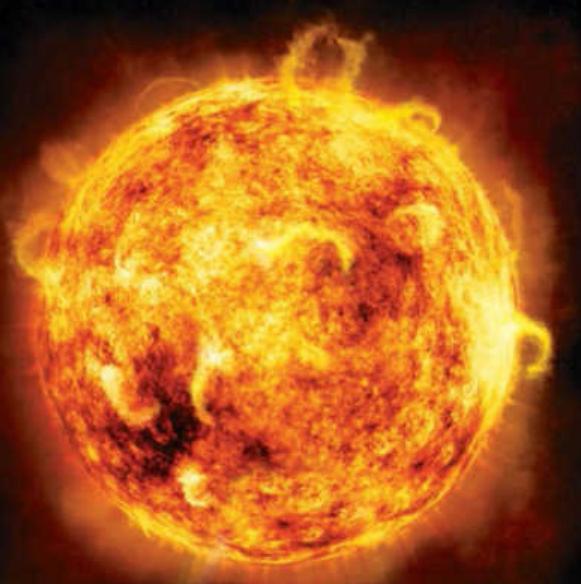
Take a tour through the incredible  
wonders of our Solar System

THE SUN • THE PLANETS • THE EARTH & MOON



# Welcome to the All About **Space** BOOK OF THE **SOLAR SYSTEM**

Over the centuries, humankind has dwelled on the question of how the Solar System came into being around 4.5 billion years ago. In the 21st Century, our pursuit of knowledge is as insatiable as ever, and new technology advances our understanding all the time. The more we know about the planetary system we live in, the closer we are to answering the conundrum of whether Earth - and humankind - are unique. Starting with the star at the heart of it all, the newly revised Book of the Solar System will take you on a guided tour of the essentials. How many rings does Saturn have? Is Mars capable of supporting life? Why is Venus described as our 'sister planet'? You will even get a closer look at our home planet and its only satellite. Discover what makes Earth's environment habitable, explore the Moon's surface and learn how the two entities interact. These questions and more are answered through essential guides accompanied by incredible imagery and illustrations, so you will soon feel at home with even our most hostile planetary neighbours!





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# Astronomer Royal

The much-celebrated Astronomer Royal Martin Rees gives some quick answers on some of the most current events in popular astronomy

**What, in your mind, is the greatest unanswered question of the solar system?**

Whether there is life somewhere away from the Earth. There may be simple life on Mars, but the most interesting place to search would be the oceans under the ice of Europa and Enceladus.

**Do you think Pluto's demotion to a dwarf planet was an important distinction to make?**

No, I don't think it mattered. If Pluto hadn't been discovered until recently, we'd have put it in the same class as several other objects in the outer Solar System (one of which is bigger than Pluto). We would therefore either call them all planets, or put them (with Pluto) in a separate category.

**Your support for the crowd-funded Lunar Mission One has been well publicised. What is there left to learn that was not achieved by the 1960-70s moon landings?**

Many parts of the moon haven't been explored. We would like to learn more geology by digging below the surface. Especially interesting are the craters near the poles which are always in darkness and therefore could have persisting ice.

**What is the probability that Earth will one day be hit by a comet or asteroid? What is the planet's chance of survival?**

We know that the kind of asteroid that probably killed the dinosaurs hits the Earth once every few tens of million years. There's about one chance in a million that that's how we'll die (i.e. if it were to come



Rees was one of the first scientists to propose that supermassive black holes were the source of a quasar's power

soon). But smaller objects hit more frequently and could devastate a city or region. There are efforts to chart the orbits of the million asteroids more than 50 metres across, to identify any that might hit the Earth. Within 50 years it may be possible to deflect the orbit of such an object so it would miss us.

**"Most of us would want to take this historic first trip to Mars, even if it is one-way"**



Rees delivers his acceptance speech at the 2011 Templeton Prize award ceremony



**INTERVIEWBIO**

**Martin Rees**

Renowned Astronomer Royal Martin Rees is best known for his work on some of the most exotic and extreme objects in the cosmos: black holes, quasars, gamma ray bursts and the early universe. He's written several books, has received numerous prestigious academic awards, he was the president of the Royal Astronomical Society and even has a seat in the UK's House of Lords, as Baron Rees of Ludlow.



HRH the Duke of Edinburgh bestows the Templeton Prize on Martin Rees



The Arecibo Observatory in Puerto Rico. Rees supports the work of SETI, but thinks it unlikely that life will be found elsewhere in the Solar System



The team behind the Planck spacecraft's Cosmic Microwave Background-exploring mission. The Big Bang theory has come far in the last 50 years

**It has been reported that you believe sending humans into space is wasteful of time and money, but what do you make of projects like Virgin Galactic aimed at creating an industry of space tourism?**

I hope people now living will walk on Mars. But they'll be embarking on a dangerous adventure. I think the phrase 'space tourism' is unfortunate as it lulls people into believing that space travel will be safe and 'routine'.

**When do you think humans will land on Mars?**  
Probably within the next 50 years.

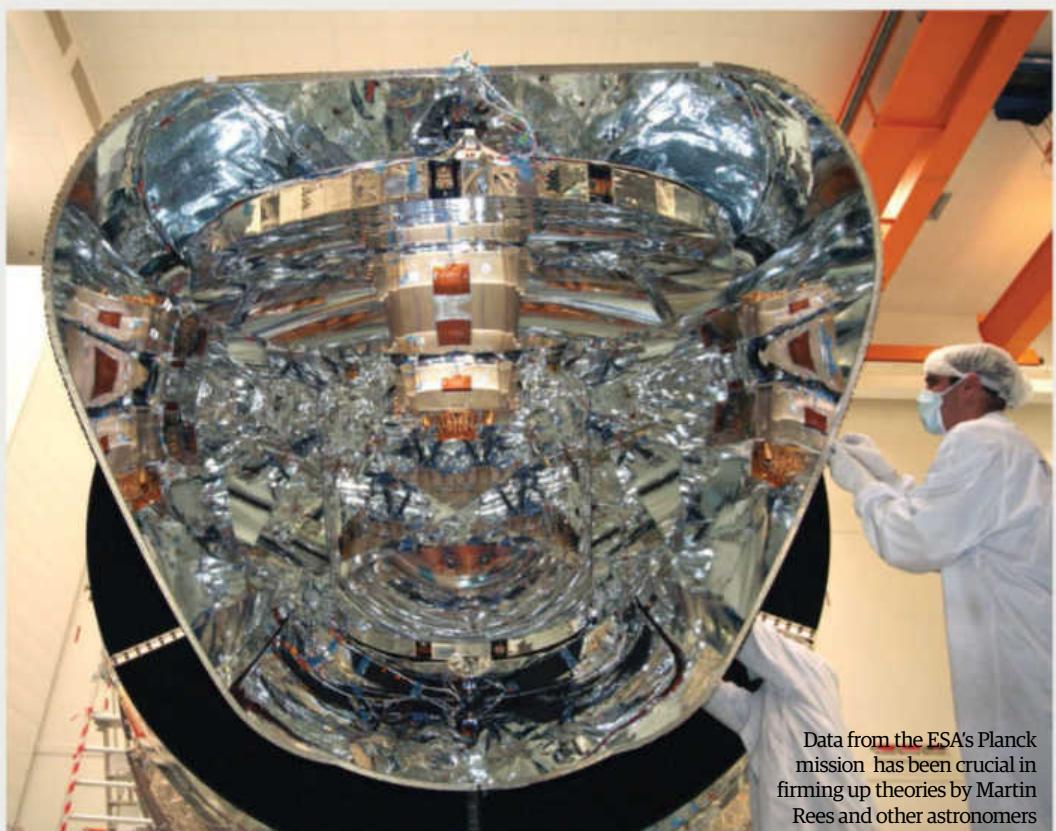
**Do you understand the desire to be among the first Mars One crew to undertake the proposed one-way journey to settle on Mars in 2026?**

Yes, I think most of us would wish to take this historic first-trip to Mars, even if they had a one-way ticket. But I'm very sceptical about anyone who claims to be able to do this by 2026.

**Do you think there is enough interest among young people to learn about astronomy?**

I'm surprised and gratified that there's so much interest - it's second only to dinosaurs in making young people aware of the mysteries of science!

**What do you make of Google's Lunar XPrize?**  
A great idea which we can all cheer on.



Data from the ESA's Planck mission has been crucial in firming up theories by Martin Rees and other astronomers

## Birth of the Solar System



# Birth of the **SOLAR SYSTEM**

How did our Solar System form? Until recently, astronomers thought they knew. But now, new research is turning many of the old ideas on their heads

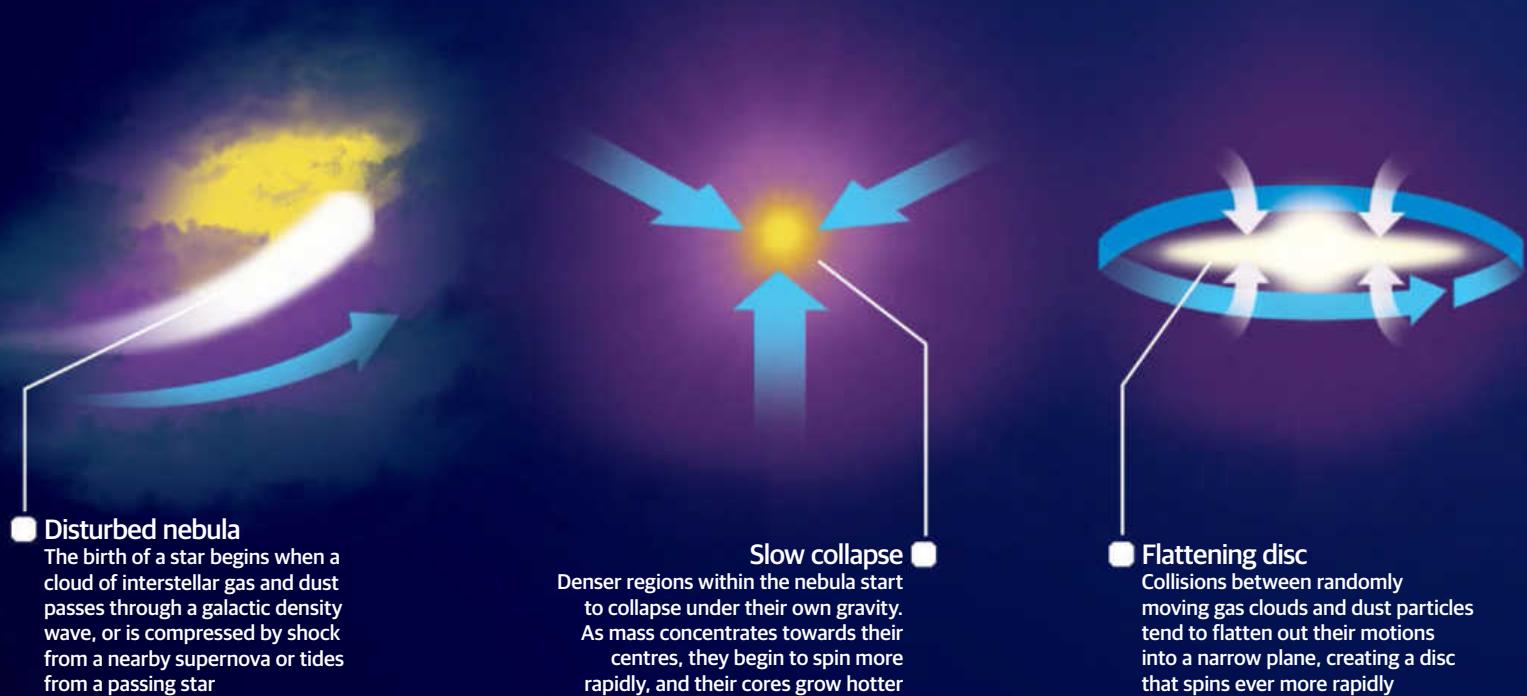
# Birth of the Solar System

Around 4.5 billion years ago, our Sun and all the other objects that orbit around it were born from an enormous cloud of interstellar gas and dust, similar to the glowing emission nebulae we see scattered across today's night sky. Astronomers have understood this basic picture of the birth of the Solar System for a long time, but the details of just how the process happened have only become clear much more recently - and now new theories, discoveries and computer models are showing that the story is still far from complete. Today, it seems that not only did the planets form in a far more sudden and dynamic way than previously suspected, but also that the young Solar System was rather different from that we know now.

The so-called 'nebular hypothesis' - the idea that our Solar System arose from a collapsing cloud of gas and dust - has a long history. As early as 1734, Swedish philosopher Emanuel Swedenborg suggested that the planets were born from clouds of material ejected by the Sun, while in 1755 the German thinker Immanuel Kant suggested that both the Sun and planets formed alongside each other from a more extensive cloud collapsing under its own gravity. In 1796, French mathematician Pierre-Simon Laplace produced a more detailed version of Kant's theory, explaining how the Solar System formed from an initially shapeless cloud. Collisions within the cloud caused it to flatten out into a spinning disc, while the concentration of mass towards the centre caused it to spin faster (just as a pirouetting ice skater spins faster when they pull their arms inwards).

**"Much of what we know about the birth of our Solar System comes from observing other star systems"**

## How stars are formed



In the broad strokes described above, Laplace's model is now known to be more or less correct, but he certainly got some details wrong, and left some crucial questions unanswered - just how and why did the planets arise from the nebula? And why didn't the Sun, concentrating more than 99 per cent of the Solar System's mass at the very centre of the system, spin much faster than it does? Solutions to these problems would not come until the late 20th Century, and some of them are still causing doubts even today.

Much of what we know about the birth of our Solar System comes from observing other star systems going through the same process today. Stars are born in and around huge glowing clouds of gas and dust, tens of light years across, called emission nebulae (well known examples include the Orion Nebula, and the Lagoon Nebula in Sagittarius). The nebulae glow in a similar way to a neon lamp, energised by radiation from the hottest, brightest and most massive stars within them, and remain active for perhaps a few million years, during which time they may give rise to hundreds of stars forming a loose star cluster. Since the brilliant, massive stars age and die rapidly, it's only the more sedate, lower-mass stars like our own Sun that outlive both the nebula and the slow disintegration of the star cluster.

Star birth nebulae develop from the vast amounts of normally unseen, dark gas and dust that forms the skeleton of our Milky Way galaxy, and subside as the fierce radiation from their most massive stars literally blows them apart. The initial collapse that kick-starts formation can be triggered in several

ways - for instance by a shockwave from a nearby exploding supernova, or by tides raised during close encounters with other stars. However, the biggest waves of star birth are triggered when material orbiting in our galaxy's flattened outer disc drift through a spiral-shaped region of compression that extends from the galactic hub and gives rise to our galaxy's characteristic shape.

Inside the nebula, stars are incubated in huge opaque pillars of gas and dust. As these pillars are eroded by outside radiation from massive stars that have already formed, they break apart into isolated dark globules whose internal gravity is strong enough to hold them together - the seeds of individual solar systems. Gas falling towards the very centre of the globule becomes concentrated, growing hotter and denser until eventually conditions are right for nuclear fusion, the process that powers the stars, to begin. As the star begins to generate energy of its own, its collapse stabilises, leaving an unpredictable stellar newborn surrounded by a vast disc of gas and dust that will go on to form its solar system. But how? That's where things get really interesting...

The first person to put Laplace's hypothesis on a sound theoretical footing was Soviet astronomer Viktor Safronov, whose work was first translated from Russian around 1972. Safronov's modified 'solar nebular disk model' allowed the Solar System to form from much less material, helping to resolve the problem of the Sun's slow spin. What was more, Safronov provided a basic mechanism for building planets out of primordial dust grains, known as 'collisional accretion'.

This simple mechanism involves small particles colliding and sticking to each other one at a time, eventually growing into objects that were large enough to exert gravitational pull and drag in more material from their surroundings. This produced

objects called planetesimals, the largest of which might have been about the size of the dwarf planet Pluto. A final series of collisions between these small worlds created the rocky planets close to the Sun, and the cores of the giant planets further from the Sun. The difference between the two main types of planet is then explained by the existence of a 'snow line' in the early Solar System, around the location of the present-day asteroid belt. Sunward of this, it was too warm for frozen water or other chemical ices to persist - only rocky material with high melting points survived. Beyond the snow line, however, huge amounts of ice and gas persisted for long enough to be swept up by the giant planets.

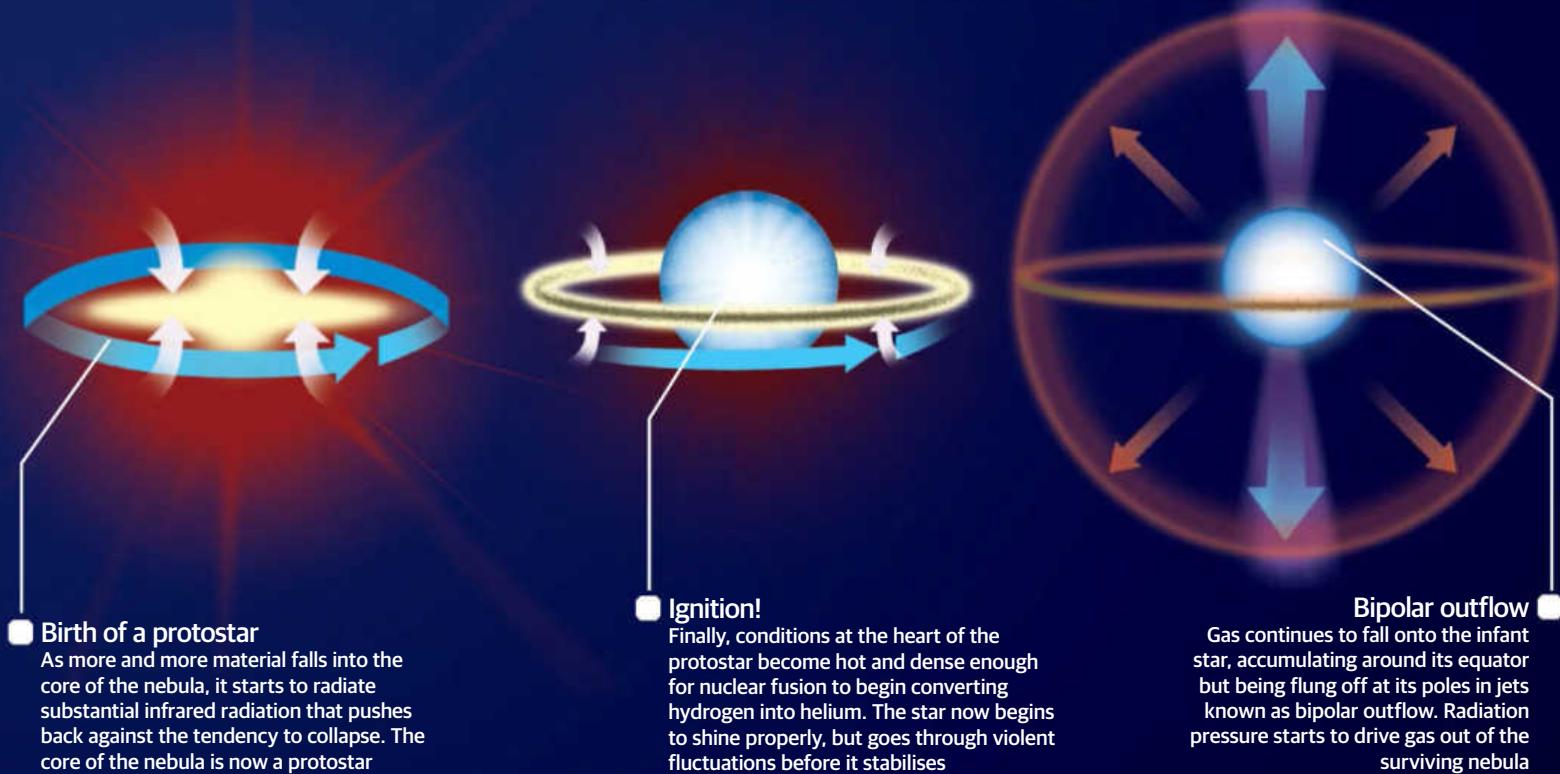
It all sounds simple enough, and has been widely accepted for the best part of four decades. But now that seems to be changing. "There's been the beginning of a paradigm shift away from the two-body build-up that Safronov modelled," says Dr Hal Levison of the Southwest Research Institute (SwRI) in Boulder, Colorado. "The idea of things growing by collisions hasn't really changed but over the last five years or so, new theories invoking the idea of pebbles [are] coming to the fore. We've really only now got to the stage where we can discuss these ideas in any great detail."

The new approach stems from a long-standing problem: "The big question is how you get the first macroscopic objects in the Solar System - things that are bigger than, say, your fist," explains Levison. "Safronov's idea was that you just did that through collisions, but people have always recognised there's a problem we call the metre barrier."

"You only have to look under your bed to see plenty of evidence that when small things hit one another, they can stick together, making these dust bunny clumps that are held together by electrostatic forces [weak attraction between innate static electric charges]. And if you look at objects bigger than, say



Known as N90, this emission nebula in the Small Magellanic Cloud shows many features associated with the birth of stars, with a central cluster dominated by heavyweight stars, and stalactite-like opaque pillars where star birth is still continuing



## The birth of the planets

Our Solar System was cooked up in a swirling cloud of gas and dust

### 1 Shapeless cloud

About 4.5 billion years ago, the raw materials of the Solar System lay in a shapeless cloud of gas and dust. Its dominant components were hydrogen and helium, but it was also enriched with elements created by previous generations of stars, and scattered through the so-called interstellar medium. These included carbon, oxygen and nitrogen, as well as dust grains (often carbon-based) up to one micrometre ( $0.001\text{mm}$  or  $4\times 10^{-5}\text{in}$ ) across

### 2 Collapse begins

The trigger event for the formation of an emission nebula typically produces condensation in several regions of the cloud that happen to have higher densities. Each may give rise to a whole group of stars – once the first stellar heavyweights have begun to shine, their radiation helps energise the nebula, and also sculpts its shape, dictating where the younger generations of stars will form. However, by blowing material out of the nebula, these early giants also stunt the growth of their siblings

### 9 The Solar System today

The neat, near-circular orbits of today's planets are an inevitable result of their formation from the merging of many objects in a disc around the Sun – while many solar systems around other stars seem to have planets in much wilder orbits, this is probably a result of later gravitational interactions and phases of planetary migration like the ones that once shaped our own Solar System

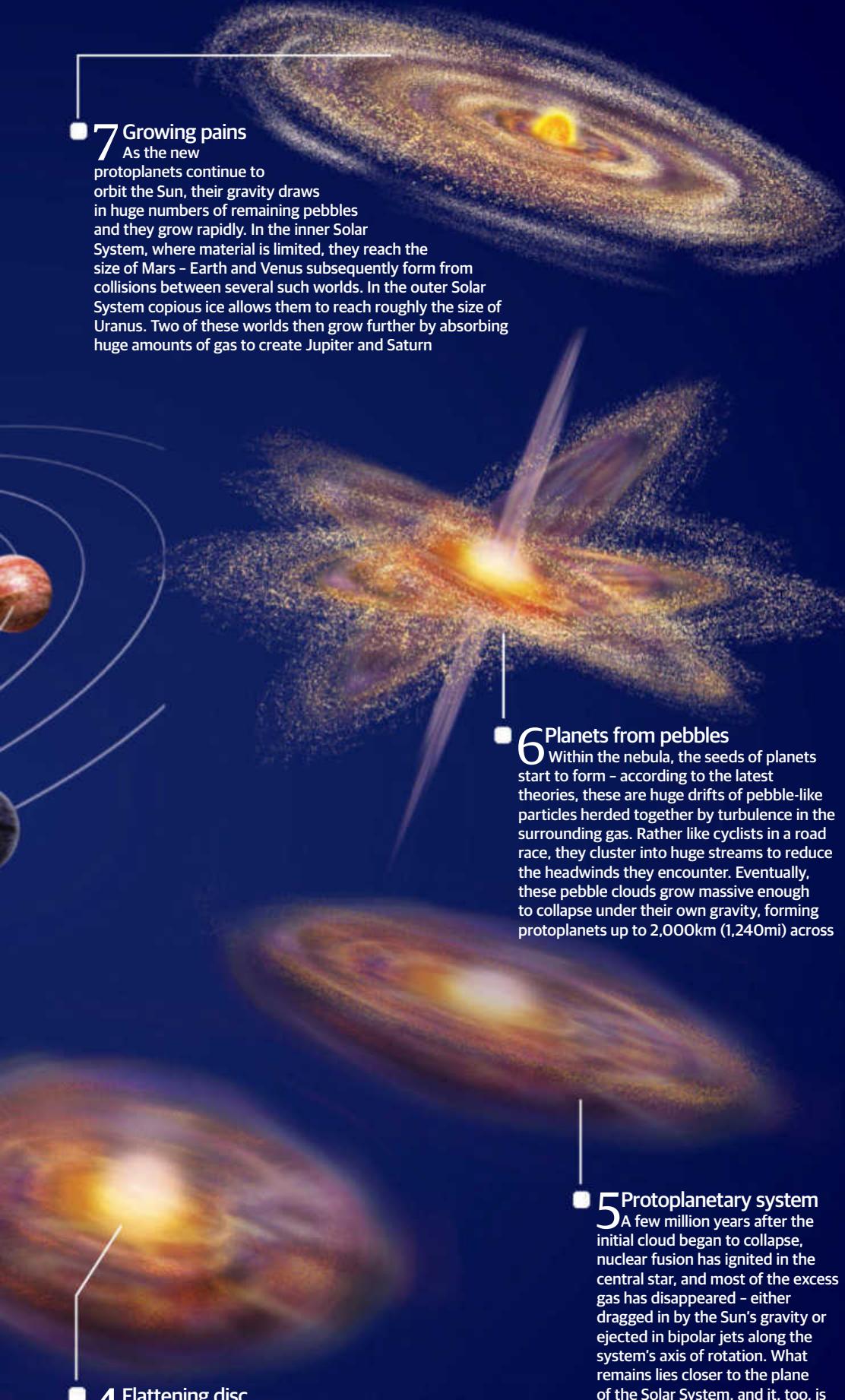
### 8 Planetary migrations

During one or more phases of planetary migration, the giant planets of the outer Solar System change their configurations and locations, moving back and forth through a host of smaller bodies (asteroids, small comets formed between the giant planets, or ice dwarfs orbiting beyond). The havoc they wreak ultimately gives rise to the modern asteroid belt, Kuiper belt and Oort cloud, though the latter may also include comets captured from other stars born alongside the Sun

"The old idea of getting to Mars-sized objects by banging Moon-sized things together could be wrong"

### 3 Individual systems

A single globule of collapsing gas and dust may give rise to a single star or a multiple star system at its centre. As material falls inward, collisions between gas clouds and particles tend to cancel out movements in opposing directions, while an effect known as the conservation of angular momentum causes the cloud's central regions to spin faster as most of the mass concentrates there



## 7 Growing pains

As the new protoplanets continue to orbit the Sun, their gravity draws in huge numbers of remaining pebbles and they grow rapidly. In the inner Solar System, where material is limited, they reach the size of Mars – Earth and Venus subsequently form from collisions between several such worlds. In the outer Solar System copious ice allows them to reach roughly the size of Uranus. Two of these worlds then grow further by absorbing huge amounts of gas to create Jupiter and Saturn

## 6 Planets from pebbles

Within the nebula, the seeds of planets start to form – according to the latest theories, these are huge drifts of pebble-like particles herded together by turbulence in the surrounding gas. Rather like cyclists in a road race, they cluster into huge streams to reduce the headwinds they encounter. Eventually, these pebble clouds grow massive enough to collapse under their own gravity, forming protoplanets up to 2,000km (1,240mi) across

## 4 Flattening disc

The end result of the cloud's collapse is a spinning disc with an orientation derived from the slow random rotation of the original globule. Dust and ice particles tend to concentrate more efficiently around the central plane of this disc, while gas forms a looser halo, and continues to fall in towards the central regions until conditions there become extreme enough to create one or more protostars

a few kilometres across, gravity can hold things together. But if you're looking at something, say, the size of a boulder, then it's hard to imagine what makes those things stick."

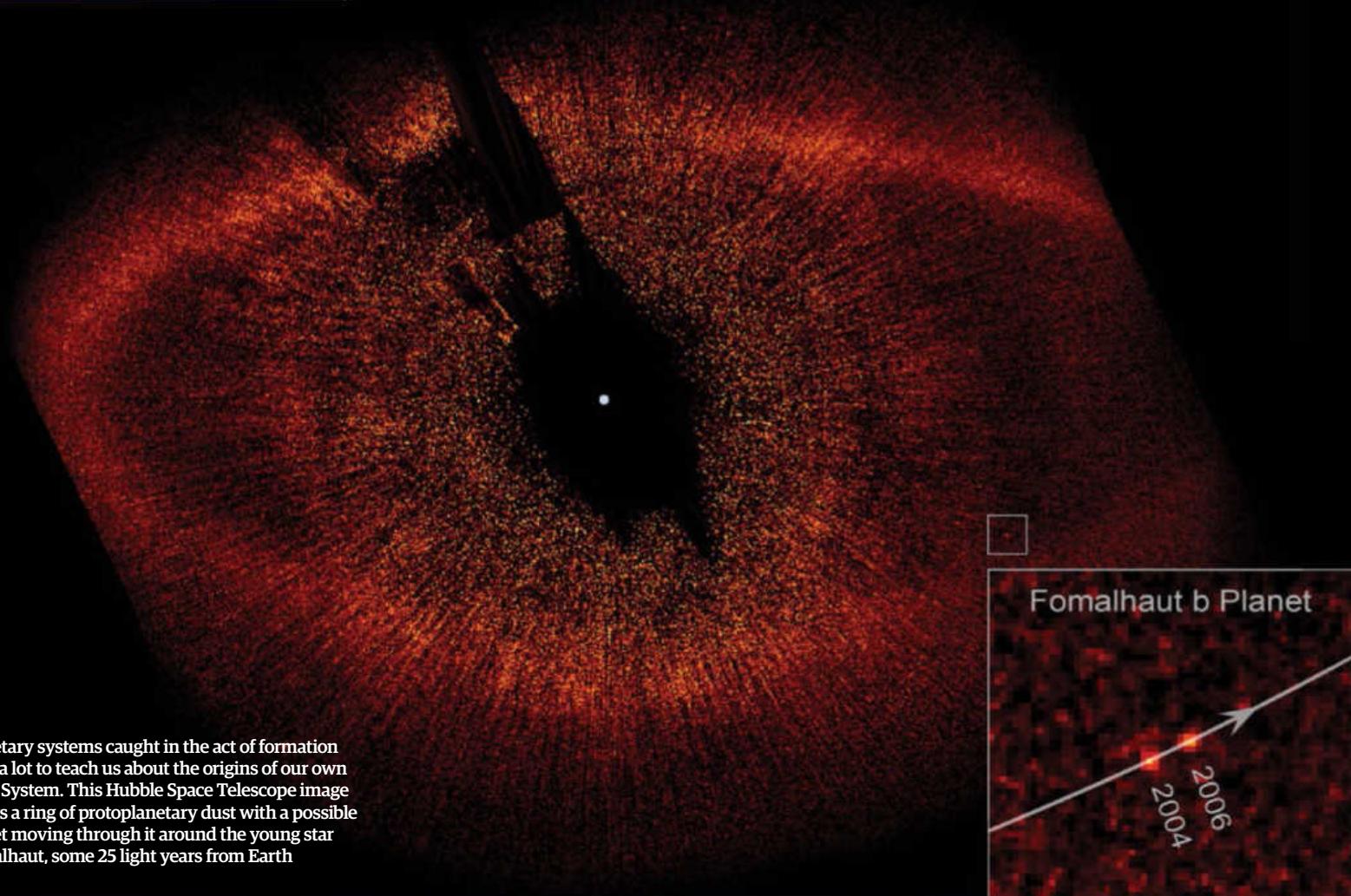
Fortunately about ten years ago, researchers including Andrew Youdin (University of Arizona) and Anders Johansen (now at Sweden's Lund University) came up with an ingenious way around the problem. "What they've shown is that as dust grains settle into the central plane of the protoplanetary disc, that causes a kind of turbulence that concentrates the pebbles into large clumps," continues Levison. "And eventually these clumps can become gravitationally unstable and collapse to form really big objects. This model predicts that you go directly from things the size of your fingernail to hundred-kilometre [62-mile]-sized objects, in just one orbit around the Sun."

Over the past few years, as various teams including Levison's group at SwRI have worked on the theory, they've found that the clumping process is even more effective than they first thought: "We're talking about objects up to the size of Pluto forming this way, out of pebbles." And that's just the first stage: "Once you get up to that size, you get a body that can grow very effectively by eating the surrounding pebbles, pulling stuff in with its gravity and maybe growing into something the size of Mars. So the old idea of getting to Mars-sized objects by banging a lot of Moon-sized things together could be wrong."

This new theory could help solve several outstanding problems with the Solar System, such as the relative ages of the Earth and Mars. "Mars seems to have formed about 2 to 4 million years after the Sun formed, while Earth formed about 100 million years later," explains Levison. The theory, then, is that Mars was entirely formed by the two stages of the pebble accretion process, while Earth still had to go through a final phase of Safronov-style planet-scale collisions in order to reach its present size.

"Pebbles can also help to explain how the giant planets formed as quickly as they did," Levison enthuses. "Most astronomers accept the 'core accretion' model for the giant planets, where you start out with four objects the size of Uranus and Neptune, and two of those then accumulate gas and grow to become Jupiter and Saturn. But the problem is that you need to build those cores before all the gas goes away. In the traditional Safronov model, that's hard to do, but again this new pebble accretion model can do it really quickly." The difference in scale between the Mars-sized rocky objects and the much larger giant-planet cores, meanwhile, is still to do with availability of raw material, with copious icy pebbles surviving only in the outer Solar System.

But there's one other big problem in matching the Solar System we know today with the original solar nebula – the positions of the planets, and in particular the cold worlds of the outer Solar System. Today, Uranus orbits at a distance of 2.9 billion kilometres (1.8 billion miles) from the Sun, and Neptune at 4.5 billion kilometres (2.8 billion miles). Beyond Neptune, the Kuiper belt of small, icy worlds (including Pluto and Eris) extends to



Planetary systems caught in the act of formation have a lot to teach us about the origins of our own Solar System. This Hubble Space Telescope image shows a ring of protoplanetary dust with a possible planet moving through it around the young star Fomalhaut, some 25 light years from Earth

## "The new pebble accretion model can help to explain how the giant planets formed as quickly as they did" **Dr Hal Levison**

more than twice that distance, and then there's the Oort cloud - a vast spherical halo of icy comets that extends to around 15 trillion kilometres (9.3 trillion miles). The solar nebula, meanwhile, would have been most concentrated around the present orbit of Jupiter, and trailed off from there - while computer models suggest Uranus and Neptune could not have grown to their present size unless they were closer to Jupiter and Saturn.

All of which brings us to the work for which Levison is perhaps best known - his contribution to the so-called 'Nice model' of planetary migration. This explains the current configuration of the Solar System as the result of the dramatic shifting of the planets that happened around 500 million years after its formation.

"The Nice model goes back some ten years now," recalls Levison. "It postulated a very compact configuration for the outer planets when they formed, with Jupiter and Saturn, probably Neptune next, and then Uranus all orbiting in the outer Solar System, and beyond that, a disc of material with the mass of about 20 Earths. The biggest objects inside that disc would have been about the size of Pluto."

In the Nice scenario, all four giant planets formed within the present-day orbit of Uranus, with the Kuiper belt extending to about twice that diameter,

yet still inside the current orbit of Neptune. But this arrangement was doomed to instability, and around 4 billion years ago, Uranus and Neptune began a series of close encounters that disrupted their orbits and put them onto new paths around the Sun.

Now, for various reasons, the orbits of Uranus and Neptune became unstable - they started having encounters with each other that threw them into orbits going all over the Solar System, and then having encounters with Jupiter and Saturn.

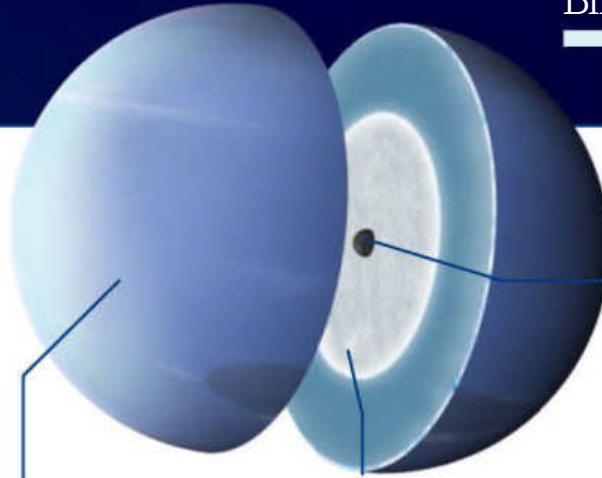
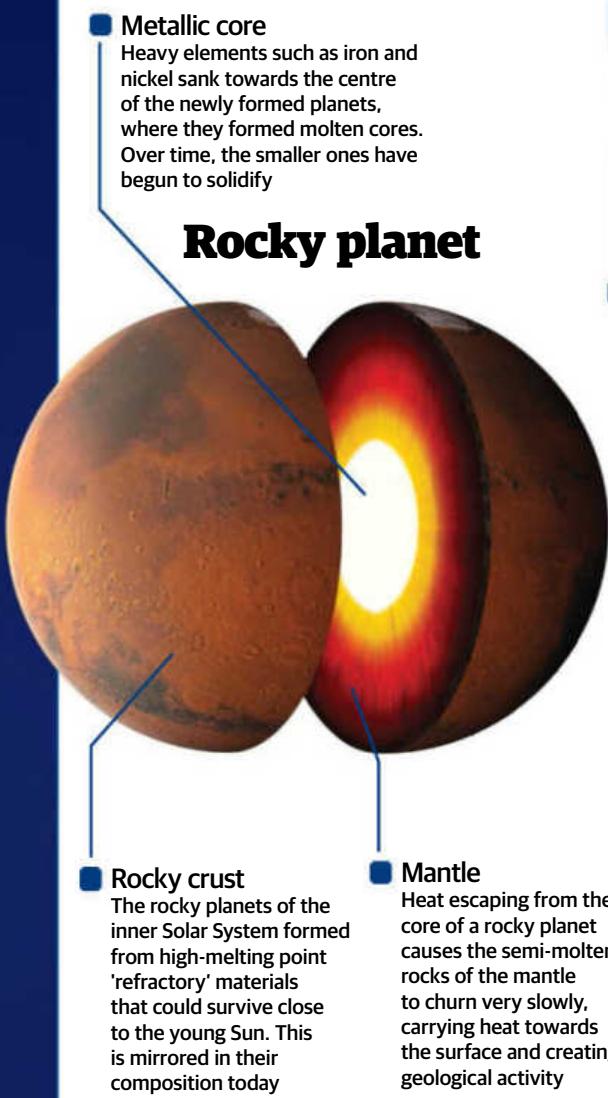
"Before too long, they began having encounters with Jupiter and Saturn," continues Levison, "and the gravity of these giant planets threw them out into the disc of Kuiper belt objects. Gravitational interactions between Uranus, Neptune and these objects circularised the orbits of the giant planets, and ejected most of the smaller objects either out into the present-day Kuiper belt, or in towards the Sun. It was a very violent, short-lived event lasting just a few tens of millions of years, and we think we see the evidence for it on the Moon, where the impact rate went up around 4 billion years ago in an event called the Late Heavy Bombardment."

Perhaps unsurprisingly, the Nice model has been tweaked a little in the decade since its first publication: "The exact mechanism that causes the instability has changed a bit, and there's work by

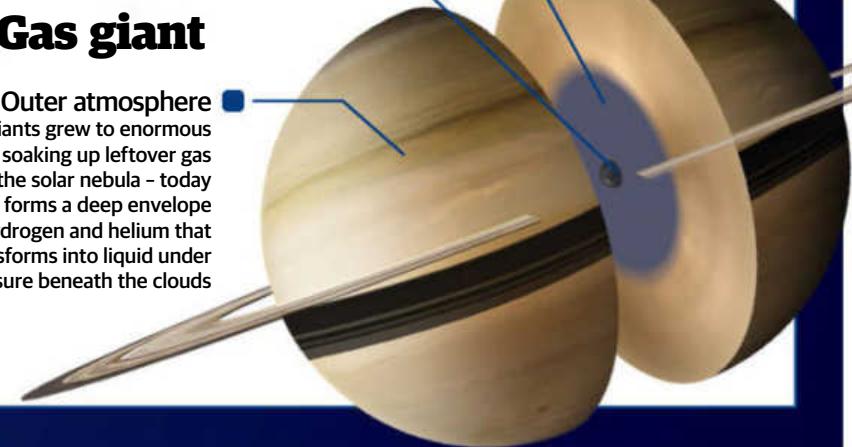


Comets are icy remnants left over from the early days of the Solar System, and may have a lot to tell us about its raw materials and early dynamics. However, Hal Levison has argued that the distant Oort cloud could also have been enriched by comets swept up from the Sun's siblings in its birth cluster

## Types of planets



## Gas giant



David Nesvorný, here at SwRI, arguing that you're more likely to end up producing the Solar System that we see if there were initially three ice giants instead of two, and we lost one during the process."

Mention of the Moon's late bombardment raises an interesting question - could some form of planetary migration also help resolve the long-standing question of where Earth's water came from? According to current theories, the environment in which the planets formed was a dry one, so the theory that our present-day water arrived later, from somewhere else in the Solar System, is a popular one. Yet measurements from comet probes such as ESA's Rosetta shows subtle but important differences from the water found on Earth.

"In fact, Jupiter wields too big of a baseball bat for comets to have made much of a contribution to water on Earth," points out Hal Levison. "Its gravity simply forms too big a barrier between the outer and inner Solar Systems, so, at most, ten per cent of water on Earth could have come from comets. We've known that for some time from dynamics

**"Jupiter wields too big of a baseball bat for comets to have made much of a contribution to water on Earth"** **Dr Hal Levison**

- we don't really need the cosmochemical measurements taken by probes like Rosetta to prove that. Instead, Earth's water probably came from objects in the outer asteroid belt, and there's a separate planetary migration model called the Grand Tack that offers one way to do that, though I think it has some problems."

The Grand Tack is part of the planet formation story itself - it involves Jupiter moving first towards, and then away from the Sun, due to interaction with gas in the solar nebula. In the process, its gravitational influence robbed Mars of the material required to grow into an Earth-sized planet, but later enriched the outer asteroid belt with water-rich bodies that might later have found their way to Earth. If that's the case, then Japan's recently

launched Hayabusa 2 probe, which aims to survey a nearby asteroid and return samples to Earth around 2020, could provide more information if it discovers Earth-like water in its target, a small body called 1999 JU3.

"The Grand Tack is one way of solving the problem of why Mars has just ten per cent of the mass of Earth and Venus, when most models predict it should be just as massive if not more so, but the pebble accretion work we're doing may also solve it," argues Levison.

It seems clear, then, that it's an exciting time for scientists probing the origins of the Solar System - who would have thought, a few short years ago, that so many answers might lie in the realm of seemingly insignificant interplanetary pebbles? ■

# LIFE in the SOLAR SYSTEM

Despite acid clouds, molten heat, deadly radiation and bitter cold, could we still be sharing our cosmic neighbourhood?





On the north-eastern border of the vast Vatnajökull glacier, Iceland, lies the Kverkfjöll mountain range, where a string of active volcanoes pepper the bleak, Icelandic landscape. Deep under the mountains, searing-hot magma gathers in cavernous chambers. Heat escaping from the chambers warms the glacial ice overhead, sculpting it into a spectacular ice cave some 2.8 kilometres (1.7 miles) long. The melted water crafts lakes that would freeze were it not for the hydrothermal energy escaping from the seething molten rock below.

These hot, acidic lakes may not seem like the most hospitable of places, but bacteria have made a home here. Ian Crawford, professor of planetary science and astrobiology at Birkbeck, University of London, studies these hardy organisms. "Part of my work is sampling the water from these boiling, acidic lakes," he says. "We want to get an insight into the adaptations that life has had to make in order to exist there." These bacteria are just one example of extremophiles - life forms that don't just survive, but actively thrive in conditions once thought incredibly hostile. Halophiles have an incredibly high tolerance to salt, xerophiles persist in some of the driest places on the planet, while alkaliphiles flourish in highly alkaline locations.

The fact that life has been found eking out an existence in remote, desolate places on Earth has raised hopes of finding life doing the same in some of the more extreme environments elsewhere in our Solar System. Ian Crawford's investigations in Iceland are helping us hunt for potentially habitable environments on Mars, for example. "Being boiled by acidic water alters the surrounding rock in a way that you can spot," he says. It's thought that the interaction between volcanoes and ice would have been a very common feature in Mars's history too. Recent Mars rovers have been equipped with instruments to detect the alterations to rock that Crawford describes, enabling them to hunt down areas on the Martian surface that could possibly have once been home to hydrothermal pools. "Mars probably isn't habitable now, but it may have been in the past," Crawford explains. Even finding evidence of long-extinct life on the Red Planet would be a remarkable achievement.

Mars is perhaps the planet that has captured the human imagination more than any other. Thanks to an army of rovers, landers and orbiters, we certainly know more about the planet than its other neighbours that we share the Solar System with. In fact, we know more about some parts of Mars than we do about parts of our own planet - we even have a better map of the Martian surface than we do of the ocean floor here on Earth. During more than ten years of orbiting Mars, the European Space Agency (ESA) Mars Express mission has imaged more than 95 per cent of the surface.

A total of four Mars rovers - robots that are driven by remote control from Earth - have been successfully deployed. Rovers Sojourner and Spirit have since been retired, while Opportunity and Curiosity are still active, with the latter recently celebrating its second anniversary of Mars exploration. Together they have revolutionised our understanding of the planet. As well as sending back glorious images, including spectacular Martian

sunsets, they have scoured the surface looking for evidence that Mars was once habitable. What they have found so far is enticing.

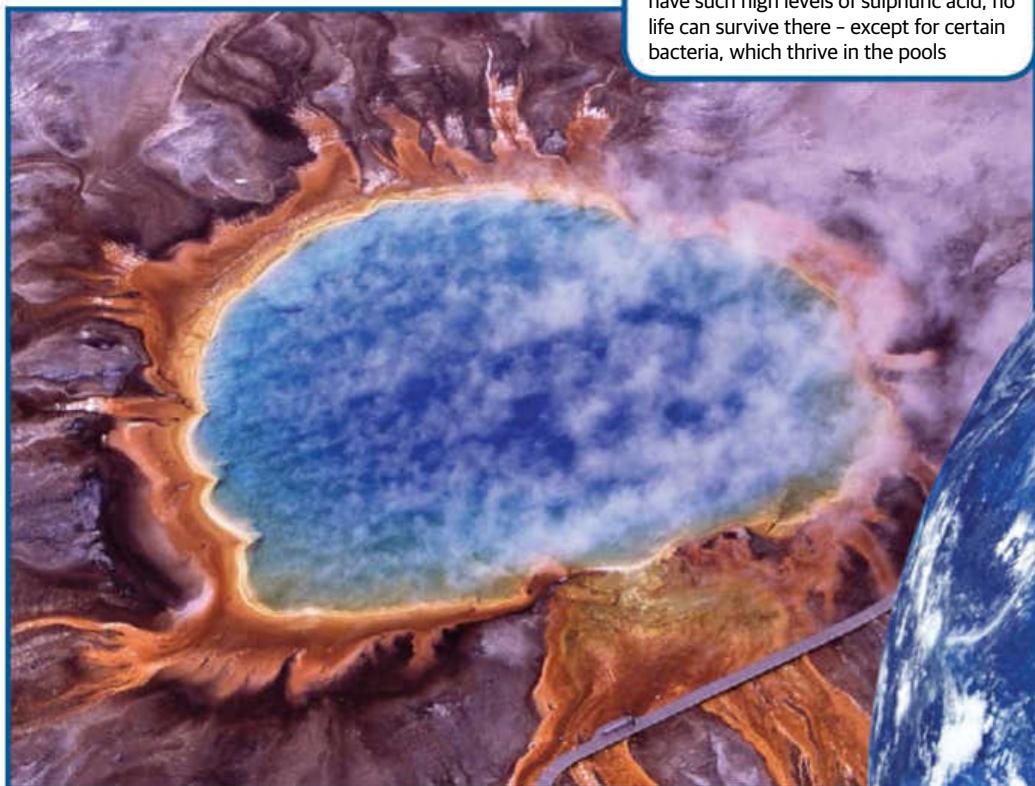
It seems that Mars used to be a warmer, wetter planet, with a much thicker atmosphere. Also, as much as a third of its surface was once covered with water. When Curiosity touched down in Gale Crater (which surrounds Mount Sharp on the Martian equator) and surveyed its new surroundings, its measurements suggested the landing site was once an expansive freshwater lake. When the rover drilled through local mudstones, it found minerals and nutrients that, coupled with the water, would have made the crater a distinctly habitable environment.

So the idea that Mars was once home to life billions of years ago is far from ridiculous. It is far more unlikely, however, that life persists on Mars today. The once wet planet is now an arid, dusty desert with only a thin atmosphere to protect any life from the many dangers of outer space. It seems the planet entered a climatic decline around 3.8 billion years ago. "Any life on the very surface would have died within a few million years, sterilised by cosmic radiation from the Sun and supernovae throughout the galaxy," says Dr Lewis Dartnell, an astrobiologist at the University of Leicester. Dartnell's work has included taking extremophiles from the Dry Valleys of Antarctica - one of the most Mars-like places on Earth - and blasting them with radiation to see how they fare. Not well, it turns out.

Contrary to popular belief, not one of the four successful Mars rovers has been equipped with instruments capable of detecting life - it's not what they were designed for. They've looked instead for evidence that the Red Planet had - or has - environments capable of supporting life. In other words, the right mix of water and nutrients, but not life itself. However, there have been two missions to Mars carrying the necessary tools to look directly for life: Viking 1 and 2 landers. The two NASA probes touched down on the Martian surface in 1976 and while they didn't move across the surface like the rovers, they were equipped with robotic arms capable of reaching out and scooping up samples of the Martian soil. These samples were then analysed for any signatures of life, but no such evidence was found by either probe.

This may be about to change, however. The first rover equipped with the right hardware to directly search for Martian life could be launched as early as 2018. ESA's ExoMars mission will have something that no previous rover has had: a sizeable drill. "ExoMars's drill will be two metres (6.6 feet) long - Curiosity's is only the length of your little finger," says Dartnell, who is working on the mission. Digging down under the Martian surface will enable scientists to probe a region where ancient life may have remained shielded from space radiation. ExoMars will

## Earth's extreme environments



### Yellowstone Hot Springs

Wyoming, USA

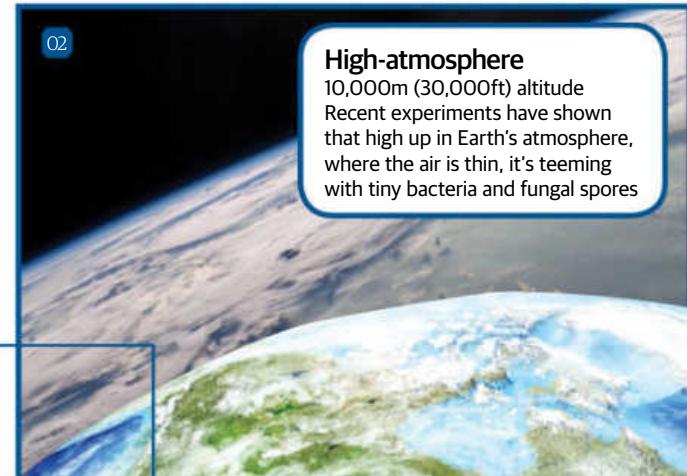
Some natural sources in Yellowstone Park have such high levels of sulphuric acid, no life can survive there - except for certain bacteria, which thrive in the pools

### Key

- 01 Acidic
- 02 Thin air
- 03 Molten heat
- 04 Extreme dryness
- 05 Freezing cold

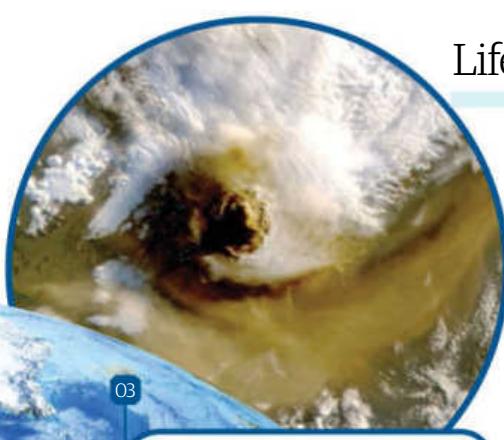


"The answer to whether life ever got started on Mars, or perhaps is still there, may one day come from intricate and innovative missions"

**High-atmosphere**

10,000m (30,000ft) altitude  
Recent experiments have shown that high up in Earth's atmosphere, where the air is thin, it's teeming with tiny bacteria and fungal spores

01



03

**Grímsvötn Volcano**

Iceland  
Some life thrives around the activity of a volcano, and bacteria have been found to breed quite happily in the boiling lakes kicked up by Iceland's grinding tectonics

**Life in the Solar System****Planetary habitats****Mars**

02 04

The Red Planet is very dry, has a thin atmosphere and once had running water on its surface. At the very least, it could have been a viable habitat for extremophile life

**Venus**

01 03

We probably don't need to look as far as the crushing pressure and heat of Venus' surface: its clouds could be a perfect environment for acid-loving organisms

**Pluto**

05

The dwarf planet is probably one of the most unlikely candidates for life in the Solar System and yet, scientists won't rule out the potential of its icy oceans

**Atacama desert**

Chile

Not much lives, grows or survives in the driest place on Earth outside of this desert's many telescope buildings, but just below the surface is a haven for bacteria



04

**Lake Vostok**

Antarctica

In a subglacial lake situated in the coldest place on Earth, living bacteria have been found, locked beneath the ice for a countless number of millennia

05

05

Sun is not being ruled out. "Conditions high up in the cloud decks aren't dissimilar to Earth. They are very acidic, but we know from studies of extremophiles on Earth that life can survive such harsh conditions," Dartnell explains.

Bacteria have already been found living high in the atmosphere on Earth, at similar heights to where human beings are only found strapped into a pressurised aeroplane cabin. Despite the much thinner air, significantly lower temperatures and increased exposure to ultraviolet radiation, bacteria are abundant there, so it's not beyond the realms of possibility that the same is true of Venus. However, unlike Earth, any Venusian life would always need to maintain its altitude - drop too low and it would be crushed, baked and dissolved.

The key question, then, is where such life would have originated. Earth's lofty bacteria are likely to have started much closer to the surface before being carried to altitude. Conditions on the Venusian surface today are too harsh to cradle life, but that might not have always been the case. "Venus may have started out similar to Earth," says Dartnell. A runaway greenhouse effect - perhaps starting just a few billion years ago - then turned it into the hellish cauldron it is today. If life got started on Venus when conditions were more favourable, some of that life may still be clinging on in the only place it can: high up in the clouds.

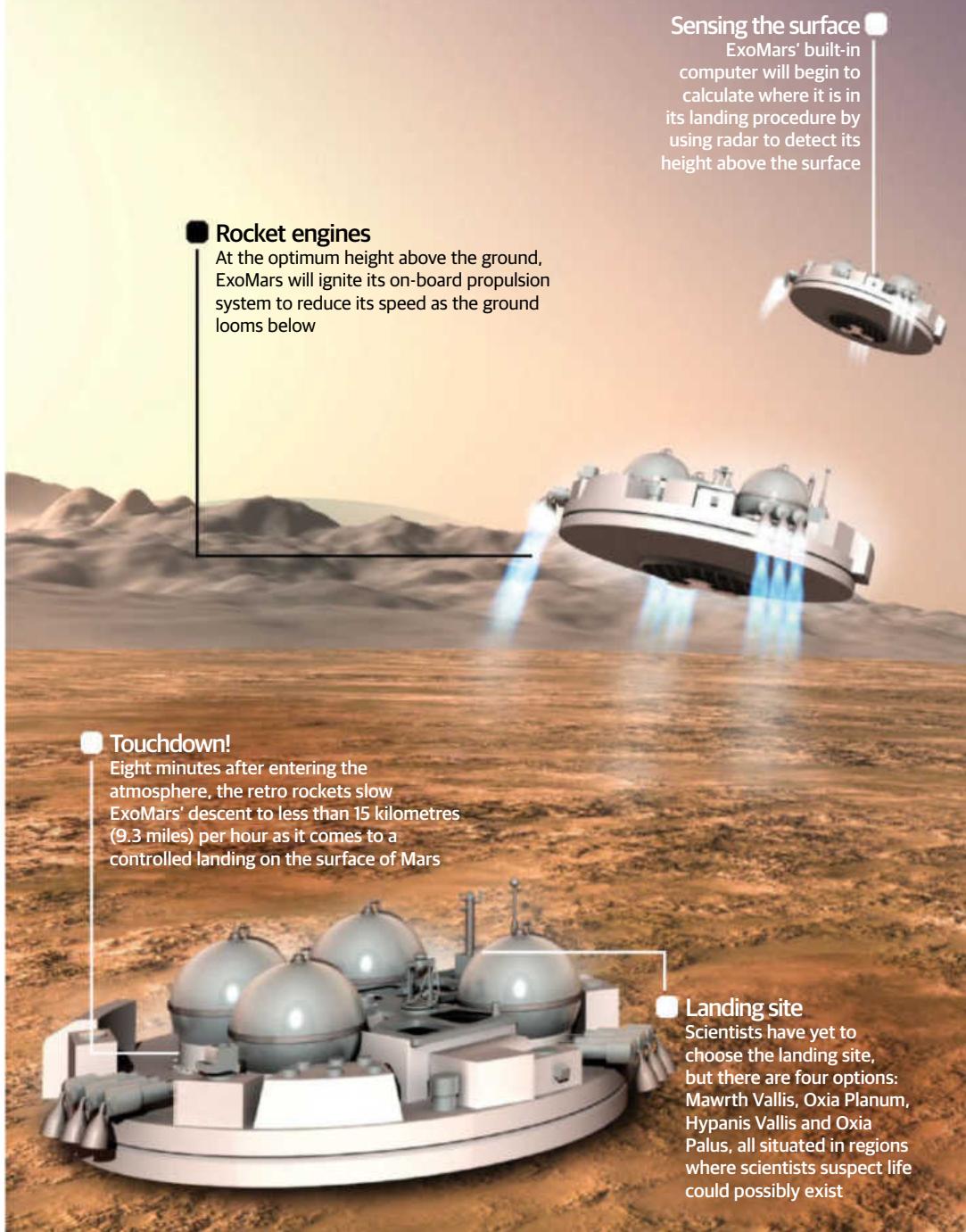
While bacterial life may be hidden away on the planets either side of us, our own planet is the one positively teeming with life. The extremophiles are an illustration of the broad range of environments life has colonised here. Almost all that life, from the tiniest bacteria to the biggest blue whale, has one thing in common: the need for liquid water. In this respect, Earth is in an ideal location. It isn't too close to the Sun, like Venus, where the temperatures soar and water evaporates. Nor do we orbit as far as Mars, where water is abundant but only persists for any length of time locked up in sprawling sheets of ice.

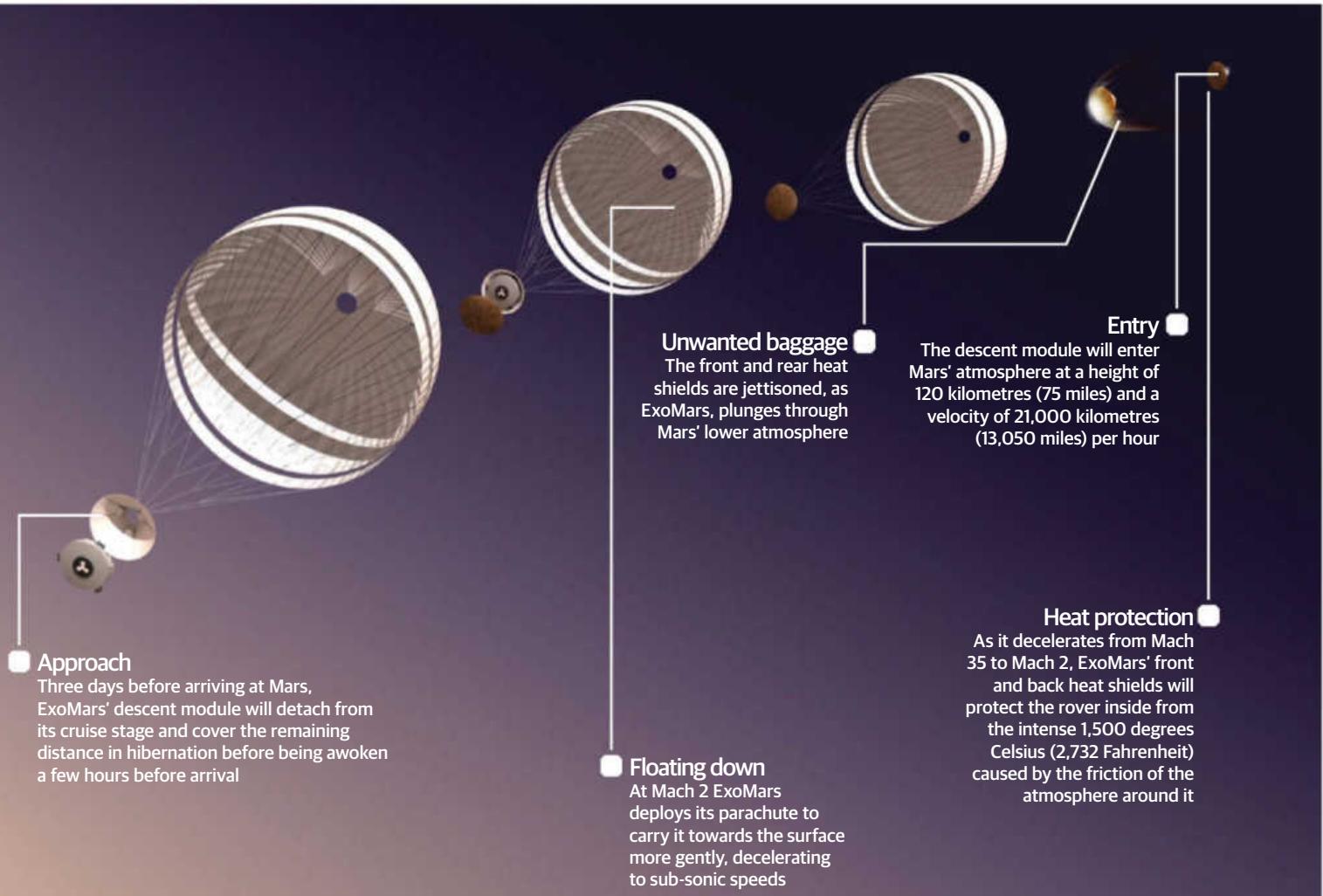
Our planet sits within the Sun's habitable zone - a thin ring of possible orbits that yields temperatures suitable for liquid water. Although not all astrobiologists agree, the alien-hunter's mantra is normally 'follow the water'. That has led to the search for alien life being extended beyond our Solar System and the hunt for Earth-like planets circling in the habitable zones of other stars. So far a total of nearly 2,000 confirmed exoplanets have been found, with a handful of them being rocky worlds in the habitable zones of their parent stars. Telescopes due to be launched in the next decade will be equipped with exquisite instrumentation capable of probing the atmospheres of these Earth-like alien worlds for signs of life. However, that doesn't mean the search is over in our own Solar System. Venus and Mars are only two of the places where life might exist, as water can be found far outside of the habitable zone too.

Given that water covers two thirds of our planet's surface, you might be forgiven for thinking Earth is the wettest place in the Solar System, but it isn't. That accolade goes to Europa, one of Jupiter's clan of 67 moons. Despite being smaller than our Moon, it is home to around twice the amount of water stored in all of Earth's oceans, lakes, seas and rivers. This water remains liquid despite being over 750 million

## Sequence of events: The touchdown of ExoMars

In order to land safely on the Red Planet, the 2018 rover needs to carry out a series of manoeuvres





# Life in the Solar System

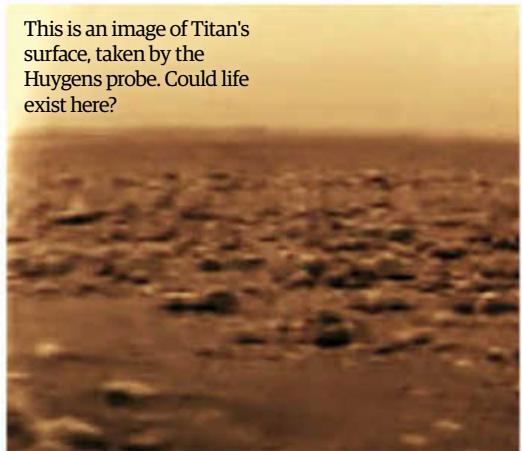
The Crybot is a probe that can penetrate kilometres-deep ice crusts to explore what's lying the oceans below



Cassini took this shot of Enceladus, spraying the contents of its interior into space



This is an image of Titan's surface, taken by the Huygens probe. Could life exist here?



kilometres (466 million miles) from the Sun - more than three times further away than the outer edge of the habitable zone. It's not our star keeping the water warm at this otherwise frigid distance, but Jupiter. Europa orbits the giant planet in just three and a half days and is mercilessly pummeled by Jupiter's immense gravity as it goes. This gravitational flexing injects enough energy into the moon's core to maintain a sizeable ocean of liquid water. The colossal gravitational tidal forces it experiences means Europa's subsurface ocean can rise and fall by as much as 500 metres (1,640 metres). The ocean is shielded from the vacuum of space by vast sheets of ice, which sport gaping cracks called lineae, caused by the Europan ocean sloshing around beneath it and cracking it up.

Any life existing in the subterranean water would be hidden away from what little solar energy reaches this part of the Solar System. That isn't necessarily a problem, because life has been found deep in our own oceans receiving no sunlight whatsoever. Instead, its energy supply is the stream of minerals seeping out of cracks in the Earth's crust on the ocean floor. Tidal heating by Jupiter may cause similar hydrothermal vents on Europa's seabed and there could even be a supply of oxygen too. One study suggests that cosmic rays hitting the surface of the ice could split some of the water into oxygen and hydrogen, some of which could end up in the cracks and filter down into the ocean below. Some questions need answering first, however. "It all depends on how thick that ice is and at the moment we simply don't know," says Dartnell. The presence of so much liquid water has led to numerous calls for scientists to



**"It's unclear whether liquid methane can be as effective a solvent for structures like DNA as water is on Earth"**

**Dr. Lewis Dartnell**

send a mission to land on the ice and explore. While no such lander is currently planned, ESA hopes to launch the Jupiter Icy Moons Explorer (JUICE) in 2022 with the intention of flying close to Europa.

The only mission to have done that so far is the Galileo probe, launched in 1989. Ever since, the small moon has commanded the lion's share of attention when it comes to habitable moons in our Solar System. But of late an even smaller, more-distant satellite - Saturn's Enceladus - has been quietly climbing the list. In 2005, the Cassini probe caught the moon spewing water plumes into space from its south pole. The water seems to be coming from four giant fissures in the moon's surface known as tiger stripes, which have been named Baghdad, Cairo, Alexandria and Damascus. Over a hundred such fountains have since been identified and it's thought that together they eject water at the rate of 200 kilograms (440 pounds) each second.

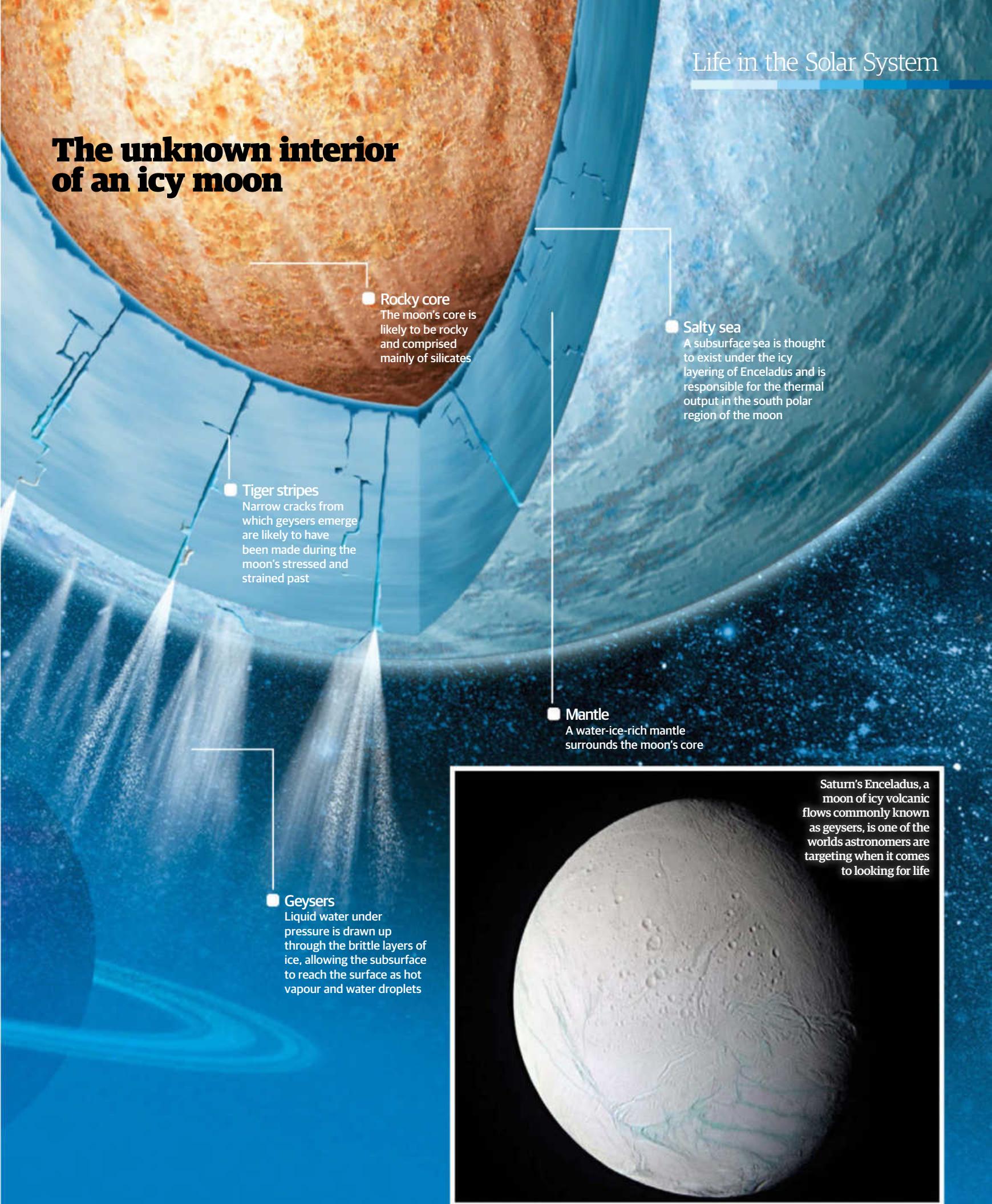
Results published by the Cassini team suggest these jets are coming from an ocean of water tucked away under the moon's icy crust. "There is enough water there to fill Lake Superior here on Earth," says lead author Luciano Iess from the Sapienza University

of Rome. So, could such an ocean be home to life? "I think Europa is a better bet than Enceladus," says Dartnell. "But Enceladus is easier to sample." As Enceladus throws some of its water into space, it's easier to access than the ice-shrouded ocean on Europa. Missions could fly through the Enceladean plumes and collect material, even returning it to Earth for detailed analysis, whereas sampling the Europan ocean would require manoeuvres.

Landing a spacecraft on the surface of an object in the outer Solar System is no mean feat. In fact, it has only been tried once before: in January 2005, the Huygens probe settled down on the surface of Titan. Saturn's largest moon and the second largest in the Solar System, Titan is bigger than the planet Mercury and it's also the only moon known to have a thick atmosphere. Like Venus, that atmosphere makes observations of the surface very difficult, so Huygens was sent through the clouds to investigate. Its findings have implications for the chances of finding life there.

Like Earth, Titan plays host to lakes, rivers and seas. It has islands, coastlines and archipelagos, yet this intricate system is not sculpted by liquid water,

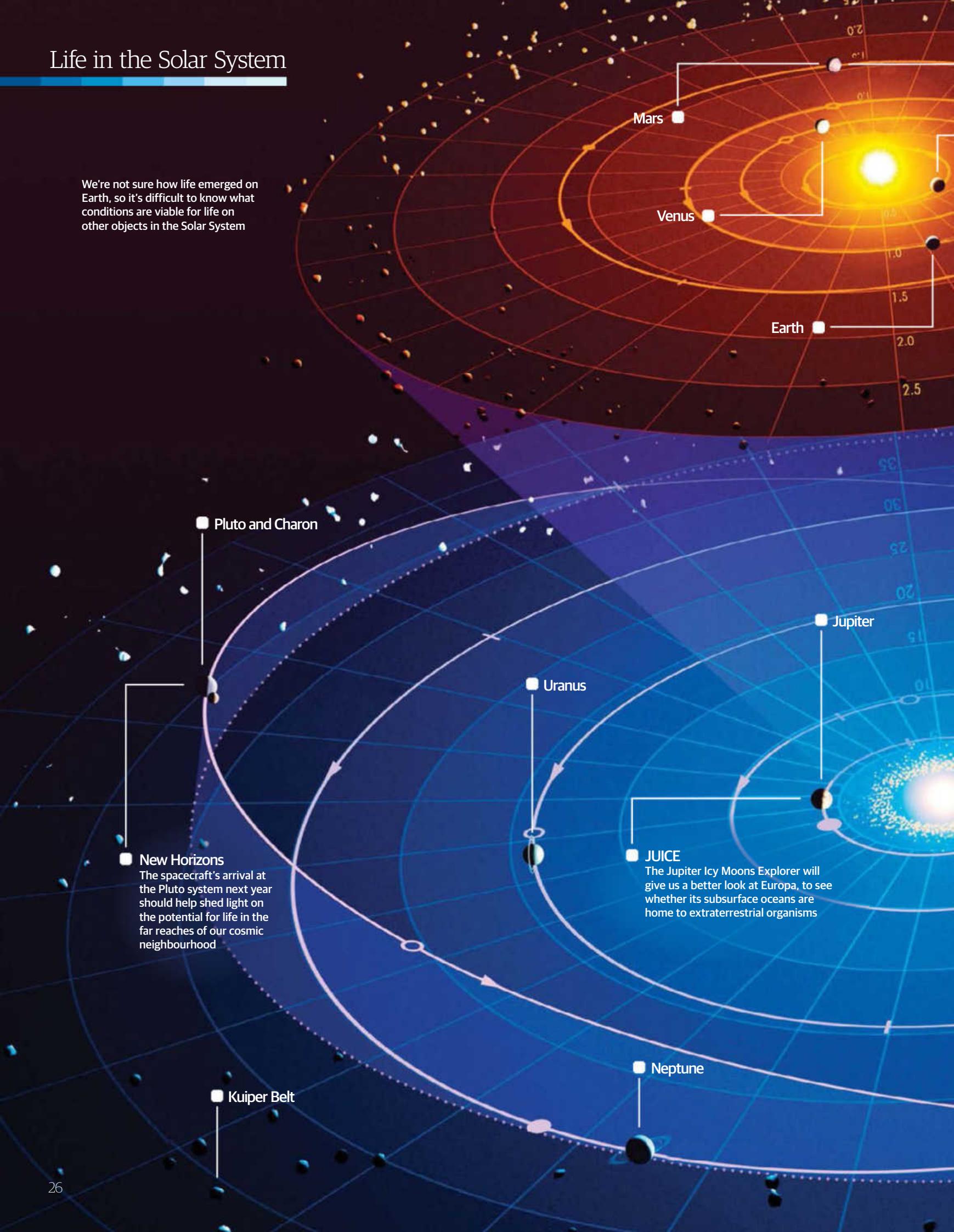
## The unknown interior of an icy moon

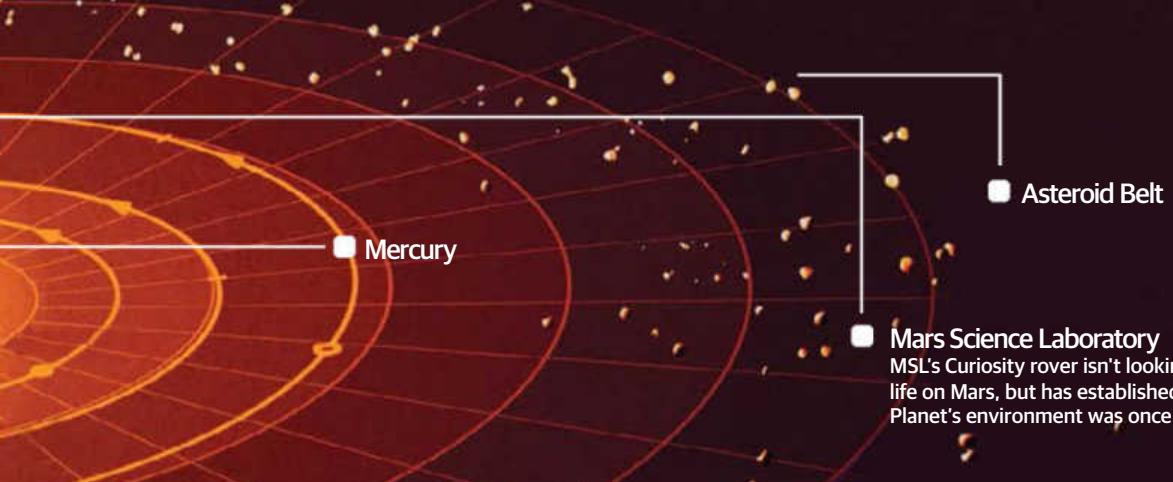


Saturn's Enceladus, a moon of icy volcanic flows commonly known as geysers, is one of the worlds astronomers are targeting when it comes to looking for life

# Life in the Solar System

We're not sure how life emerged on Earth, so it's difficult to know what conditions are viable for life on other objects in the Solar System





## "We still have a lot of work to do in order to understand what makes a suitable habitat for life"

but by liquid methane, which rains down to the surface as water does on Earth. Hydrocarbons – the building blocks from which life is constructed – have also been spotted. However, it remains to be seen if life can develop under such alien circumstances. "It's unclear whether liquid methane can be as effective a solvent for structures like DNA as water is on Earth," says Dartnell.

Titan still has liquid water – it just isn't on the surface. In July 2012, scientists using five years' worth of Cassini data found evidence that the moon probably has a sub-surface ocean comprised of liquid water and ammonia. It's thought this reservoir is incredibly salty, perhaps as salty as the Dead Sea here on Earth. But once again extremophiles have shown us that life can adapt to high salinity, particularly if the water was less salty in the past. "It would make Titan a unique place, perhaps with not one biosphere, but two," says Dartnell. If this is the case, it is possible that these two ecosystems could have developed entirely independently of each other.

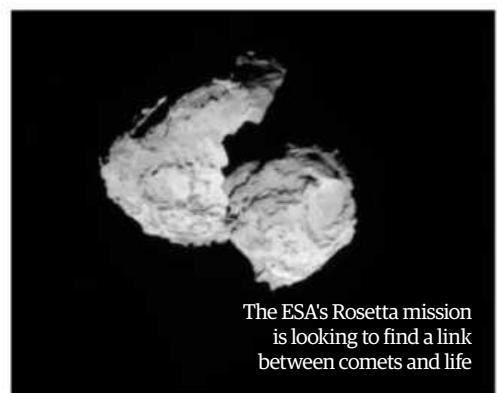
If chemicals other than water are being considered as solvents capable of sustaining life, another world to look at might be Triton – Neptune's largest moon. The temperature here plummets to just -235 degrees Celsius (-391 Fahrenheit), too cold even for methane to remain liquid. However, it's believed that an ocean exists beneath its icy crust. Ice volcanoes on the surface eject what scientists believe to be liquid nitrogen and methane. Hydrocarbons are thought to exist here too, although that might not be enough to make the moon habitable. "Triton is the outside bet because no one knows if liquid nitrogen can sustain life," says Dartnell.

What makes Triton particularly interesting is that it's the only sizeable moon in the Solar System to orbit its planet backwards – in the opposite direction to the spin of its host. It's very hard to envisage how such a big moon could have formed spinning backwards around its planet, so the leading theory is that Triton was captured by Neptune's gravity some time after the planet formed. The moon's most likely birthplace is the Kuiper Belt – an area of icy bodies that includes the dwarf planet Pluto. This region is home to at least twenty times more material than the Asteroid Belt between Mars and Jupiter. Beyond the Kuiper Belt sits the scattered disc – the origin of short-period comets such as the famous Halley's

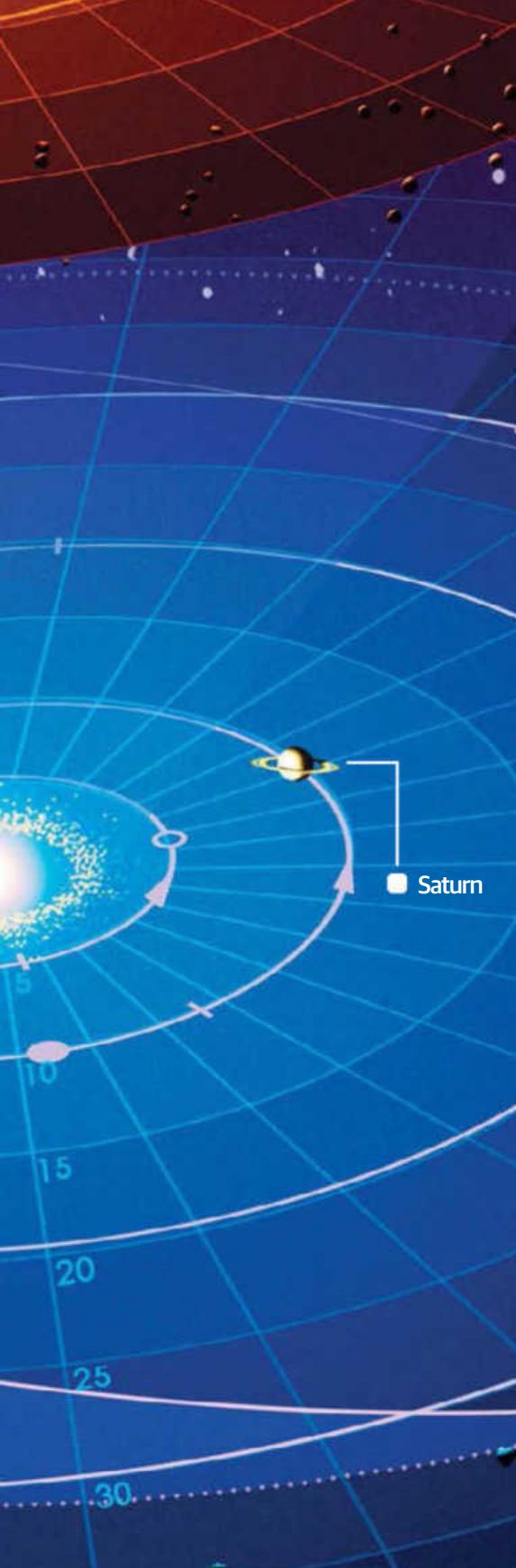
comet. Studies of both comets and asteroids have shown that they contain complex organic molecules that might be capable of acting as the building blocks for life. Missions like ESA's Rosetta – which linked up with comet 67P/Churyumov-Gerasimenko after a ten-year, 400-million-kilometre (250-million-mile) journey – hope to discover more about the link between comets and life.

During the Solar System's youth, its planets and moons were battered by a deluge of comet and asteroid impacts over an era known as the Late Heavy Bombardment period. Objects like Mercury and the Moon still bear the scars of these collisions today. It's possible that they even seeded the infant Earth with the right range of chemicals from which life would later develop. If that is true, then it's very likely other places in our Solar System were seeded too. The answer to the question of whether those seeds turned into living organisms elsewhere has been the driving force behind much of our exploration of our local space neighbourhood so far, and will continue to be in future.

However, our searching to date has shown that we still have a lot of work to do in order to understand what makes a suitable habitat for life. Earth is still the only place we know of capable of supporting living things, yet we still don't even know for sure how life on our planet began. Knowing what turned a set of inanimate chemical ingredients – possibly delivered by comets – into something we'd describe as living, would be a big step in determining whether that has happened on other worlds, both in our Solar System and even beyond. ■



The ESA's Rosetta mission is looking to find a link between comets and life



# The Sun

Discover the star at the centre of our Solar System

## **30 All about the Sun**

Explore the star that keeps us all alive

## **42 Fusion power Sun**

Learn about harnessing the Sun's energy resources to generate power

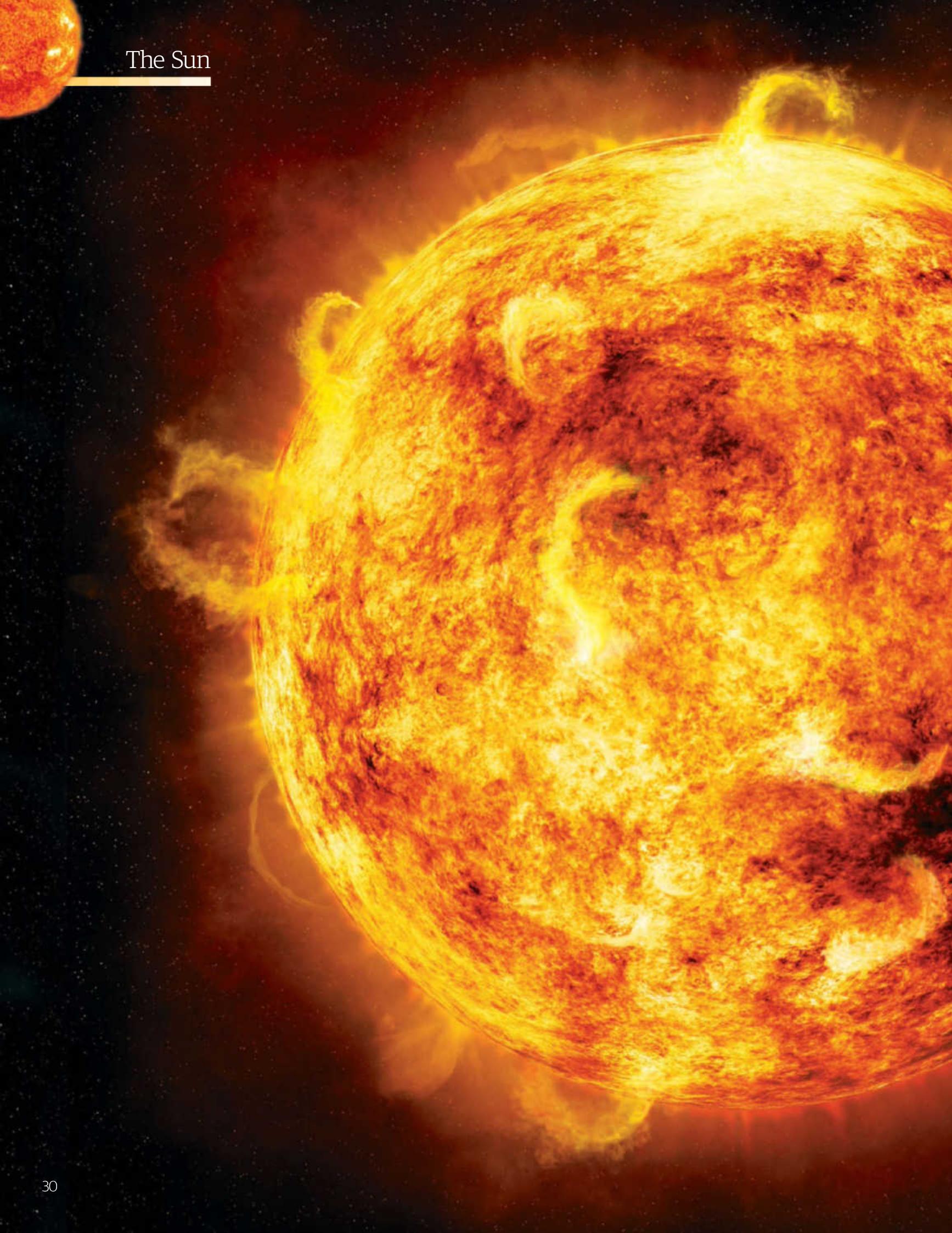
## **50 The Sun's twin star**

Kick-start the search for extraterrestrial life



**"A solar flare is a sudden increase in the brightness on the surface of the Sun"**





## The Sun

# All About... THE SUN

The vast nuclear furnace that we know as the Sun is responsible for dictating the seasons, climate and characteristics of every planet in the Solar System. Here, we take an in-depth look at this source of power that has astounded humanity since the dawn of existence

# The Sun

At about 150 million kilometres (93 million miles) from Earth lies a giant incandescent ball of gas weighing in at almost 2,000 trillion trillion kilograms and emitting power equivalent to 1 million times the annual power consumption of the United States in a single second. Since the dawn of Earth, 4.6 billion years ago, it has been the one ever-present object in the sky, basking our world and those around us in energy and light - and providing the means through which environments, and ultimately life, can flourish. We see it every day and rely on its energy to keep our planet ticking, but what exactly is this giant nuclear reactor at the centre of the Solar System that we call the Sun?

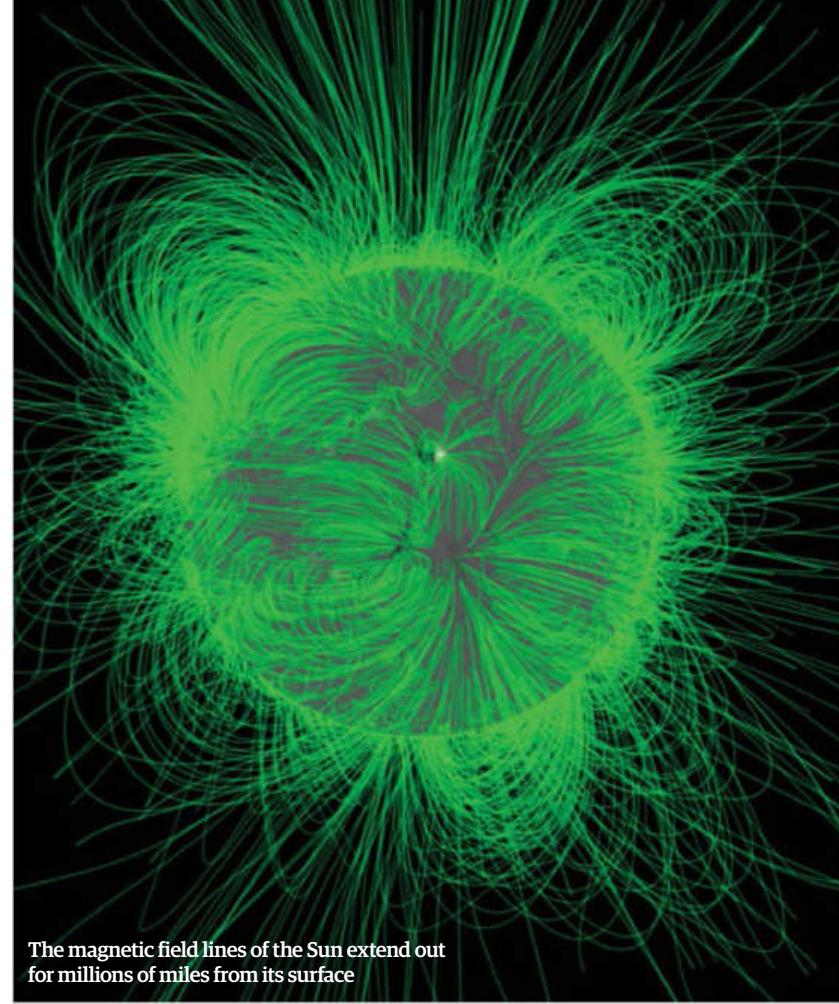
Over 5 billion years ago, a vast cloud of dust and gas was located where our Solar System is now. Inside this nebula something huge was happening; gravity was pulling together the debris, likely the remnants of another star going supernova, into one central mass. As the various metals and elements were brought together, they began to fuse into an object at the heart of this nebula. This dense clump of matter, called a protostar, grew and grew in size until it reached a critical temperature due to friction, about 1 million degrees Celsius (1.8 million degrees Fahrenheit). At this point, nuclear fusion kicked in and our Sun was born.

At the heart of the Sun, hydrogen atoms fused together to produce helium, releasing photons of light in the process, which extended throughout the Solar System. Eventually the hydrogen and helium atoms began to fuse and form heavier elements such as carbon and oxygen, which in turn formed key components of the Solar System, including humans. To us, it's the most important object in the sky. An observer watching from afar, however, would see no discerning qualities of our star that would make it stand out from any of the other

hundreds of billions of stars in the Milky Way. In the grand scheme of things it's a fairly typical star that pales in comparison to the size of others. For instance, Sirius, the brightest star in the night sky, is twice as massive as the Sun and 25 times more luminous, while Arcturus, the fourth brightest object in the night sky, is almost 26 times the size of our closest star.

The Sun is located at a mean distance of 150 million kilometres (93 million miles) from Earth, a distance known as one astronomical unit (1 AU). This giant nuclear furnace is composed mostly of ionised gas and drives the seasons, ocean currents, weather and climate on Earth. Over a million Earths could fit inside the Sun, which is itself held together by gravitational attraction, resulting in immense pressure and temperature at its core. In fact, the core reaches a temperature of about 15 million degrees Celsius (27 million degrees Fahrenheit), hot enough for thermonuclear fusion to take place. The intense physical process taking place in the Sun produces heat and light that radiates throughout the Solar System. It's not a quick process, though. It takes more than 170,000 years for energy from the core to radiate outwards towards the outer layers of the Sun.

Our Sun is classified as a yellow dwarf star, and these stars range in mass from about 80 per cent to 100 per cent of the mass of the Sun, meaning our star is at the upper end of this group. There are also three further groups into which stars are classified: Population I, II and III. Our Sun is a Population I star, which denotes that it contains more heavy



The magnetic field lines of the Sun extend out for millions of miles from its surface

elements compared to other stars (although still accounting for no more than approximately 0.1 per cent of its total mass). Population III stars are those that formed at the start of the universe, possibly just a few hundred million years after the Big Bang, and they are made from pure hydrogen and helium. Although hypothesised, no such star has ever been found, as the majority of them exploded as supernovae in the early universe, and led to the formation of Population I and II stars, the latter of which are older, less luminous and colder than the former.

By now you're probably thinking our Sun is insignificant, but that's anything but the case. Being our closest star, and the only one we can study with orbiting telescopes, it acts as one of the greatest laboratories available to mankind. Understanding the Sun allows us to apply our findings to research here on Earth, such as nuclear reactors, and our observations of distant stars. Over the next few pages we'll delve into the reasons why studying the Sun is so important and explore some of the amazing physics going on inside and outside this vast nuclear furnace. ■

**"The core reaches a temperature of about 15 million degrees Celsius, hot enough for thermonuclear fusion to take place"**

## The planets in relation to the Sun



**Spicules**  
These supersonic jets of hot plasma form in the Sun's interior and rise to a height of around 5,000km (3,000 mi) above the Sun's photosphere

**Coronal Mass Ejections**  
A Coronal Mass Ejection (CME) is a burst of plasma and magnetic fields, known as stellar wind, being thrown into space from the Sun's corona

**Faculae**  
Produced by concentrations of magnetic field lines, these bright spots appear on the Sun's chromosphere in regions where a sunspot will form

**Granulation**  
The Sun often appears granulated in images because of convection currents in its photosphere and chromosphere

**Prominences**  
These large loops of energy extend outwards from the Sun's corona. They can range over 700,000km (430,000 mi), approximately the radius of the Sun

**Sunspot**  
These dark spots on the surface of the Sun are caused by intense magnetic fields and are usually accompanied by a solar flare or CME

Our Solar System is located in the outer reaches of the Milky Way galaxy, which has roughly 200 billion stars  
Scutum-Centaurus arm  
Outer arm  
Perseus arm  
Orion spur  
The Sun

## Layers of the Sun

**Photosphere**  
The visible surface of the Sun, the photosphere, has a temperature of 5,530°C (9,980°F) and is made mostly of convection cells, giving it a granulated appearance

**Inner core**  
Most of the Sun's fusion power is generated in the core, which extends outwards from the centre to about a quarter of the Sun's radius

**Corona**  
The outer 'atmosphere' of the Sun. It is made of plasma, extends millions of kilometres outwards and has a higher temperature than the inner photosphere

**Chromosphere**  
This thin layer about 2,000km (1,240 mi) thick sits just above the photosphere and is the area where solar flares and sunspots are visible

**Radiative zone**  
This area is full of electromagnetic radiation from the core that bounces around as photon waves. It makes up about 45 per cent of the Sun

# Solar storms

Like the Earth, the Sun has an atmosphere, but the two are very different. The Sun's can be incredibly volatile with powerful magnetic activity that causes phenomena referred to as solar storms here on Earth

Solar storms are violent outbursts of activity on the Sun that interfere with the Earth's magnetic field and inundate our planet with particles. They are the result of outpourings of energy from the Sun, either in the form of a Coronal Mass Ejection (CME) or a solar flare. The former is a release of a large amount of material, mostly plasma, from the Sun, while the latter is a sudden release of electromagnetic radiation commonly associated with a sunspot. While no direct connection has been found between CMEs and solar flares, both are responsible for

causing solar storms on Earth. The reason why these two events occur is due to the Sun's atmosphere and its turbulent interior, with all of its components playing a part in bathing our planet in bursts of energy.

The lowest part of the atmosphere, the part directly above the Sun's radiative zone, is the photosphere. This is the visible part of the Sun, which is 300-400 kilometres (180-240 miles) thick and has a temperature of about 5,530 degrees Celsius (9,980 degrees Fahrenheit). This produces a white glow, although from Earth this usually

appears yellow or orange due to our own atmosphere.

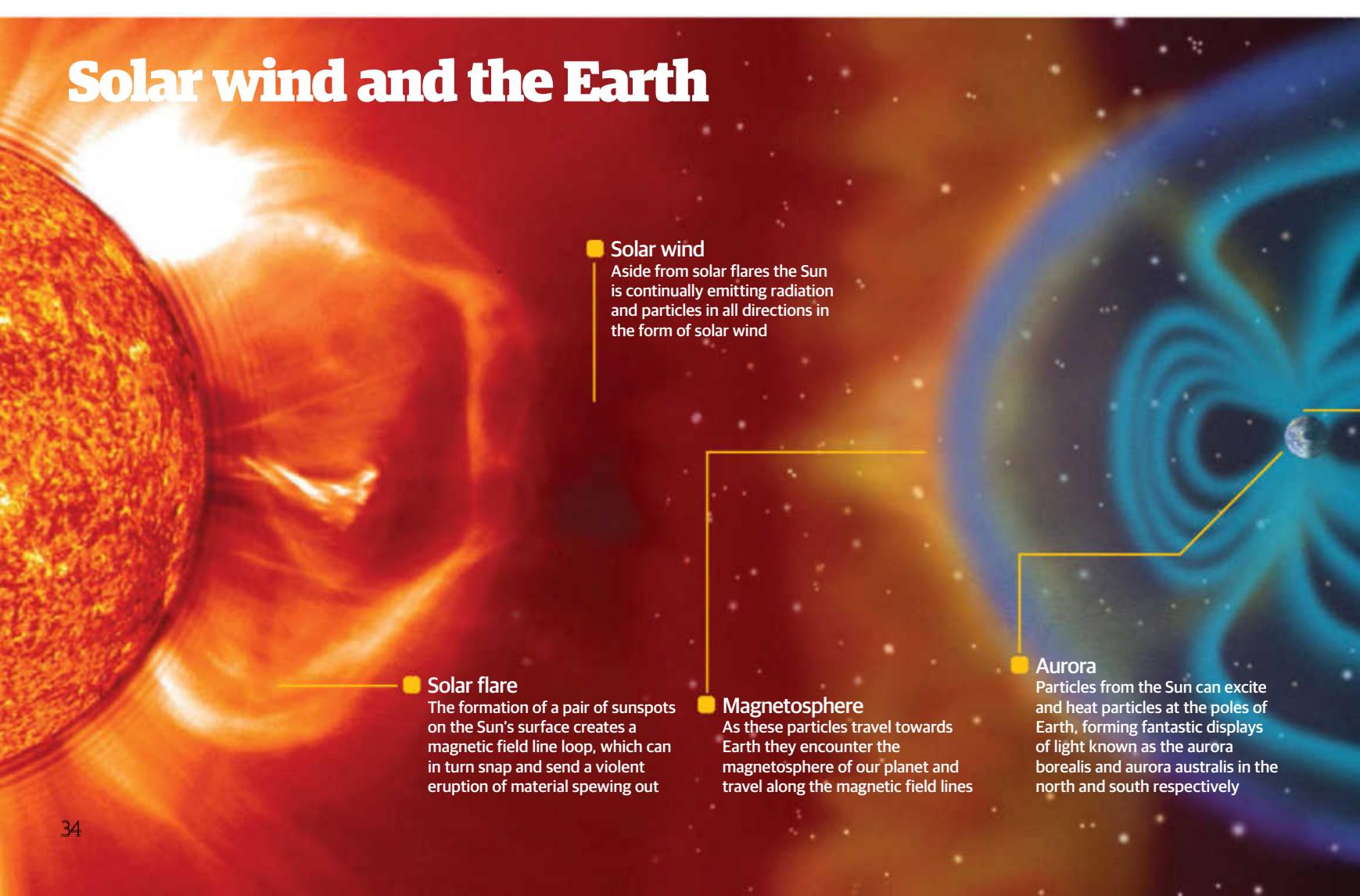
As you travel through the photosphere, away from the Sun's core, the temperature begins to drop and the gases become cooler, in turn emitting less light. This makes the photosphere appear darker at its outer edges and gives the Sun an apparently clearly defined outer boundary, although this is certainly not the case as the atmosphere extends outwards much further.

Once you pass through the photosphere you enter the

chromosphere, which is about 2,000 kilometres (1,240 miles) thick. Here the temperature rises to about 9,730 degrees Celsius (17,540 degrees Fahrenheit). The reason for this is that the convection currents in the underlying photosphere heat the chromosphere, producing shock waves that heat the surrounding gas and send it flying out of the chromosphere as tiny spikes of supersonic plasma known as spicules.

The final layer of the Sun's atmosphere is the corona. This huge expanse of material can stretch as far

## Solar wind and the Earth



### Solar wind

Aside from solar flares the Sun is continually emitting radiation and particles in all directions in the form of solar wind

### Solar flare

The formation of a pair of sunspots on the Sun's surface creates a magnetic field line loop, which can in turn snap and send a violent eruption of material spewing out

### Magnetosphere

As these particles travel towards Earth they encounter the magnetosphere of our planet and travel along the magnetic field lines

### Aurora

Particles from the Sun can excite and heat particles at the poles of Earth, forming fantastic displays of light known as the aurora borealis and aurora australis in the north and south respectively



**"Once you pass through the photosphere you enter the chromosphere, which is about 2,000km thick"**

as several million miles outwards from the surface. Oddly, the temperature of the corona averages a whopping 2 million degrees Celsius (3.6 million degrees Fahrenheit). The reason for this is unknown. As far as we are aware, atoms tend to move from high to low temperatures and not

vice versa, so the process of material moving out of the Sun beyond the photosphere is not understood.

On the photosphere, dark and cool regions known as sunspots appear in pairs as a result of intense magnetic fields. The magnetic fields, caused by gases moving in the Sun's interior, leave one sunspot and enter another. Sunspot activity rises and falls in an 11-year cycle, as discussed in the next section. Sometimes clouds of gases from the chromosphere will follow these magnetic field lines in and out of a pair of sunspots, forming an arch of gas known as a solar prominence. A prominence can last up to three months and may extend up to 50,000 kilometres (30,000 miles) above the surface of the Sun. Once they reach their maximum height they break and erupt, in turn sending massive amounts of material racing outwards through the corona. This is an event known as a Coronal Mass Ejection (CME).

When the sun's magnetic field is concentrated in sunspot areas, the resultant magnetic field lines can extend and snap, causing a violent explosion on the surface of the Sun called a solar flare. At the moment of eruption, vast amounts of radiation are emitted into space, which we call a solar storm when it reaches Earth. The particles within a solar storm often interact with particles in the atmosphere of planets in the Solar System, causing fantastic displays of light at their poles as the gases in the planet's atmosphere are heated by the particles. On Earth we know these as the aurora borealis in the Northern Hemisphere and the aurora australis in the Southern Hemisphere.

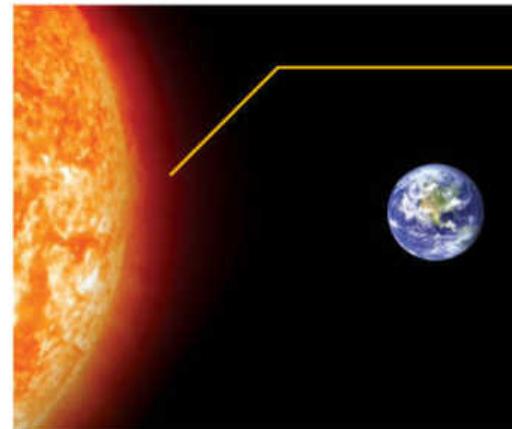
#### Poles

The particles ionise the atmosphere of the Earth, particularly at the poles where they have followed the magnetic field lines



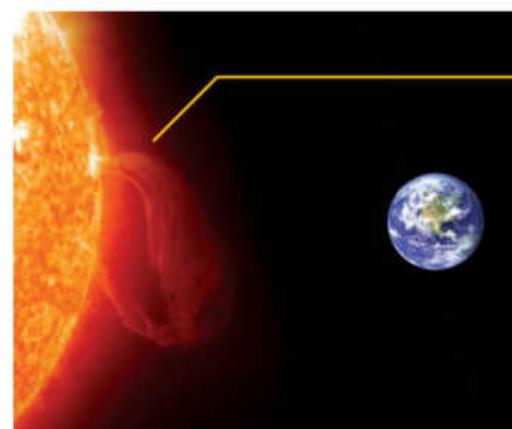
## How solar storms work

Vast amounts of radiation heading for Earth



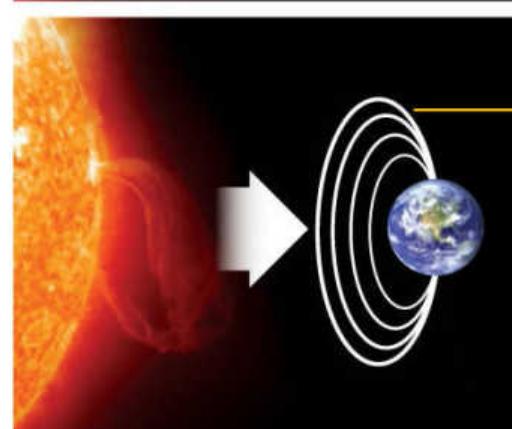
#### Explosion

A solar flare can release up to  $6 \times 10^{25}$  joules of energy as it explodes from the surface of the Sun. The giant clouds of radiation and particles can take up to two days to travel to the Earth



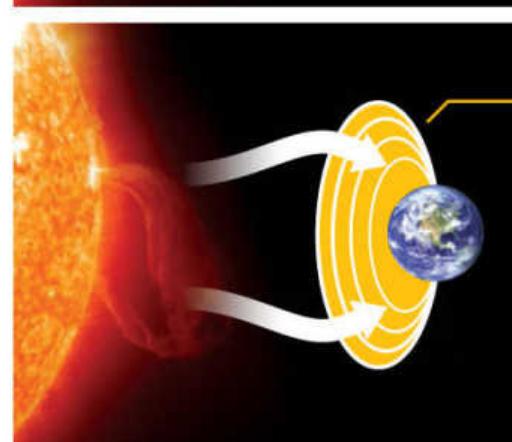
#### Cycle

Solar flares peak in 11-year-long activity cycles. The cause of these cycles is unknown. In periods of inactivity there can be less than one flare a week, but when the Sun is at its busiest there can be several every day



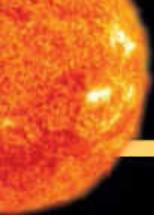
#### Intensity

Solar wind typically travels at 1.6 million kph (1 million mph), but the explosive event that emits a solar flare can send it hurtling towards the Earth up to four times faster



#### Magnetosphere

The magnetic field surrounding the Earth acts as a barrier from the Sun's activity, but some of the particles travel along the magnetic field lines and excite particles in our atmosphere, in turn causing auroras to form at the poles



# The solar cycle

Our Sun is ever-changing, affecting all life on Earth and our natural environment

Our Sun may be a great distance away, but its fluctuations and perturbations are still felt here on Earth.

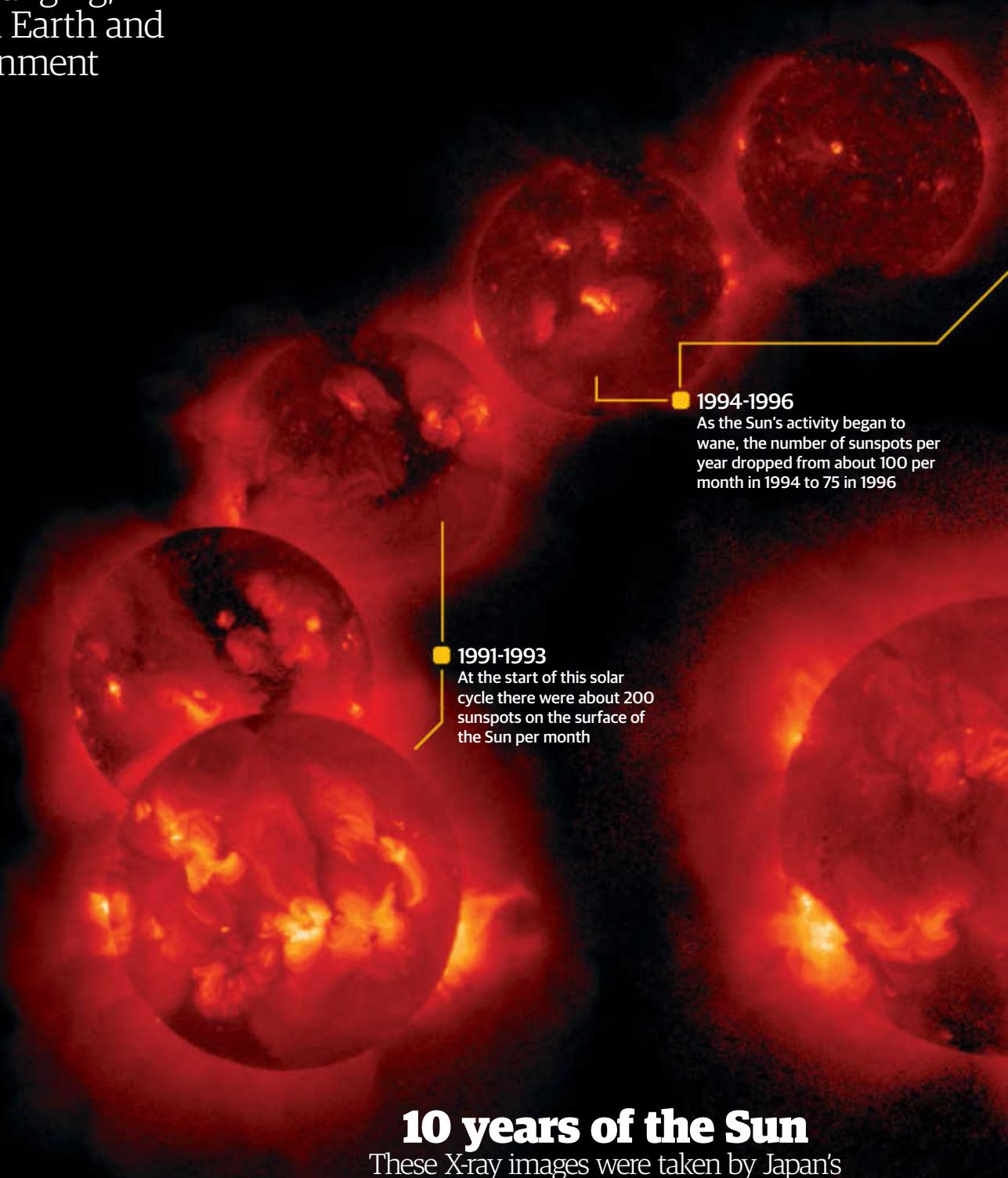
Every 11 years the Sun moves from a period of low activity, known as a solar minimum, to a period of high activity, known as a solar maximum, and back again. When it is at its most active, the Sun is even more violent than usual, with a greater number of sunspots appearing on its surface, and therefore more solar flares emitted into space. During its minimum point it is still a raging inferno firing material into space but, by comparison, it is much quieter and sunspots, and therefore solar storms, are rare.

Cycles are observed by monitoring the frequency and position of sunspots on the Sun. When the Sun reaches the end of its cycle, new sunspots will appear near the equator. The beginning of the next cycle will see sunspots appear at higher latitudes on the surface of the Sun.

Solar cycles have been observed for centuries, but a standardised method of counting them was not devised until 1848 when Johann Rudolf Wolf started counting sunspots on the solar disk and calculated the Wolf number, which is still used today to keep track of the solar cycle. From 1645 to 1715 there were few sunspots present on the Sun, a period known as the Maunder Minimum.

The number of sunspots has been relatively more uniform this century, with cycles having an average period of 10.5 years. The Sun also has a 22-year magnetic cycle where, every 22 years, its magnetic field flips from pole to pole. This doesn't have a noticeable effect on the Solar System, but indicates when the solar maximum of the current cycle has been reached.

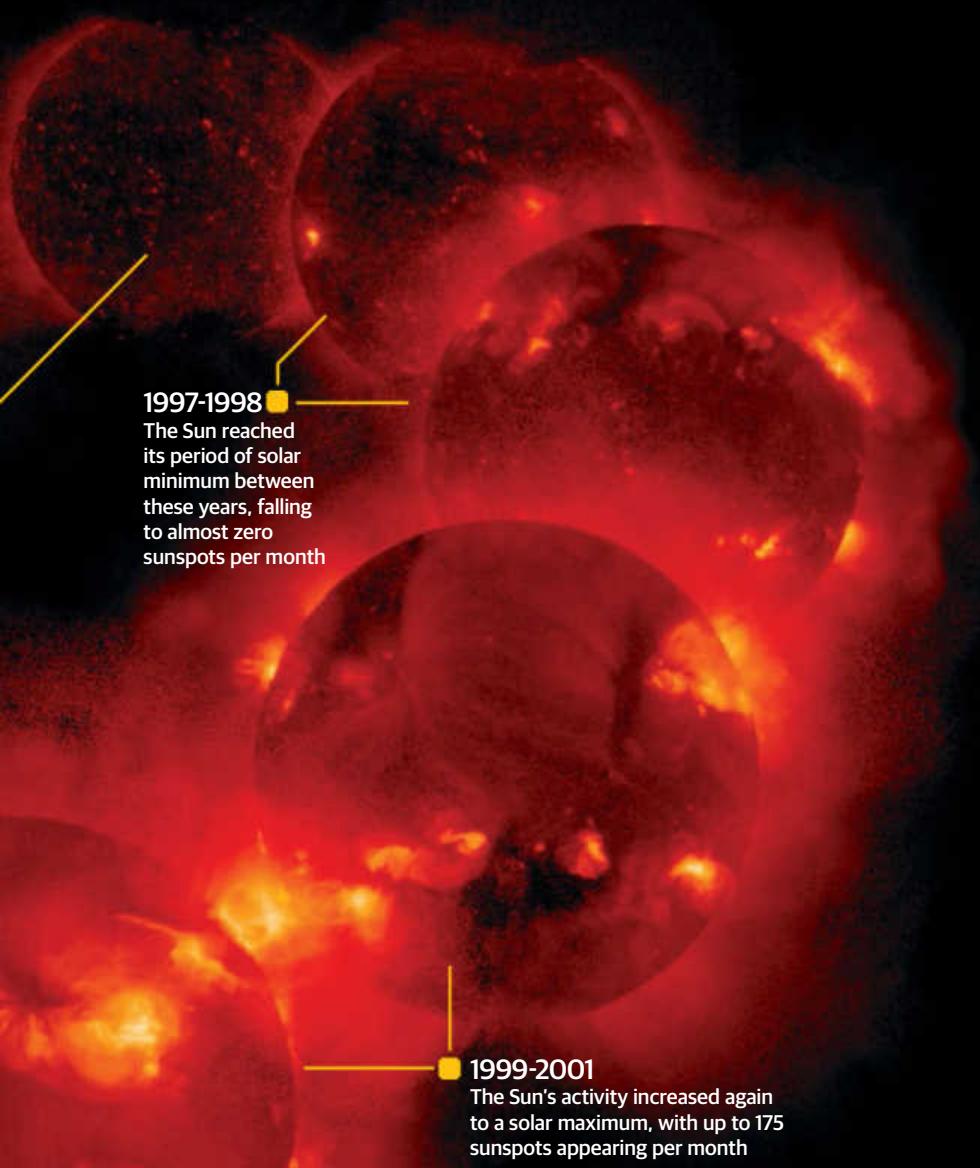
However, the reason behind these cycles remains a mystery, and no one yet has any clear understanding as to why the Sun has these periods of varying activity.



## 10 years of the Sun

These X-ray images were taken by Japan's Yohkoh Solar Observatory and show the changes in the Sun's corona over a ten-year cycle between 30 August 1991 and 6 September 2001

"Solar cycles have been observed for centuries, but a method of counting them was not devised until 1848"



#### The Scientist's view

#### How we understand solar cycles

"Sun-Earth interaction is complex, and we haven't yet discovered all the consequences of solar cycle variation on Earth's environment. We saw a large amount of geomagnetic activity driven by recurring fast solar wind streams during the recent solar minimum. A surprising departure from the consistently low activity we'd come to expect from previous minima, especially considering the record low level of sunspots. These new observations deepen our understanding of how solar quiet intervals affect the Earth and how and why this might change from cycle to cycle."

Sarah Gibson, UCAR, @AtmosNews



## The Sun in numbers

Fantastic figures and surprising statistics about our nearest star

**99.86%**

*The Sun's percentage of mass of the entire Solar System*

Less than **5%**  
of stars in the Milky Way are brighter or larger than the Sun

**1**  
**million**  
**Earths**  
Would fit inside the Sun

**164**  
**watts** Is the amount of energy every square metre of the Earth's surface receives. That's the equivalent of a 150-watt table lamp on every square metre of the Earth's surface

**498 seconds**  
How long it takes light to travel from the Sun

**100 BILLION**  
Tons of dynamite would have to be detonated every second to match the energy produced by the Sun

# The SOHO mission

The Solar and Heliospheric Observatory was launched in December 1995 and is helping us explore the Sun

## Interview



SOHO  
project  
scientist  
Bernhard  
Fleck tells us why  
studying the Sun is  
important to Earth

### 1. Understand life

"The Sun provides the energy for all life on Earth. It seems quite natural that we are curious to know more about the star from which we live."

### 2. Understand climate

"Solar radiation is the dominant energy input into the terrestrial ecosystem. The Sun provides a natural influence on the Earth's atmosphere and climate. To understand mankind's roles in climate change, the Sun's impact must be understood."

### 3. Predict space weather

"Our Sun is very dynamic and produces the largest eruptions in the Solar System. These solar storms can reach our planet and adversely affect technologies such as satellites and power grids. Space weather becomes increasingly important as our society depends more on modern technologies."

### 4. Learn about stars

"If we want to understand the universe, we have to understand the evolution of galaxies. To understand galaxies, we need to understand the evolution of stars that make up the galaxies. If we want to understand stars, we better understand the Sun, the only star we can resolve in great detail."

### 5. Stellar physics lab

"The Sun lets us study basic physical plasma processes under conditions that can't be reproduced on Earth."

The Solar and Heliospheric Observatory, also known as SOHO, was launched on 2 December 1995. It was built in Europe by prime contractor Matra Marconi Space, which is now EADS Astrium. The spacecraft is operated jointly by the ESA and NASA. It studies the Sun in depth, all the way from its deep core to its outer corona and its solar wind.

SOHO is made of two modules, the Service Module and the Payload Module. The former provides SOHO with power, while the latter houses all of the instruments on the spacecraft. Overall, there are 12 instruments on board SOHO, nine of which are run by Europe as well as three from the United States.

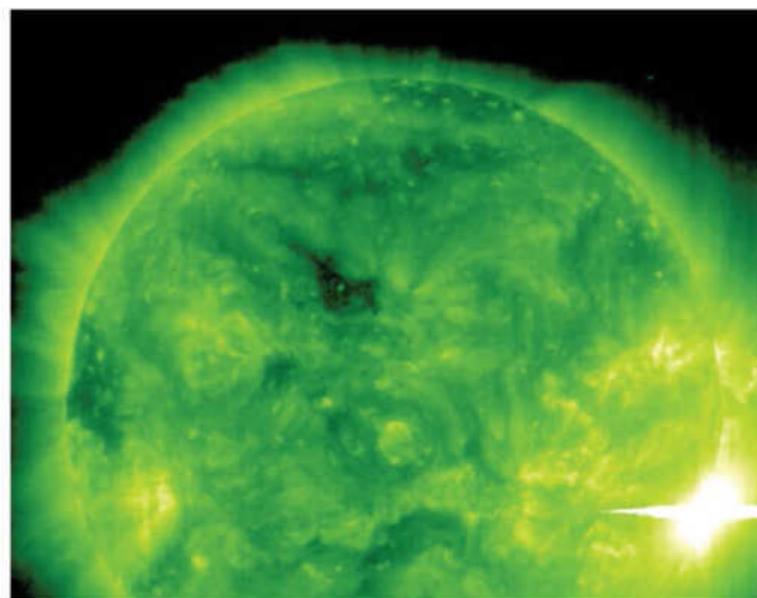
SOHO is located near to Lagrangian point 1, which is a point between the Earth and the Sun about 1.5 million kilometres (930,000 miles) from our planet. It is the point where the gravitational attraction of the Sun and the Earth cancel out, so a telescope such as SOHO can remain in a stable orbit to observe the Sun. SOHO is one of the only telescopes currently

capable of detecting incoming solar flares that could be potentially hazardous to satellites and other electronics on Earth.

Of the 12 instruments on board SOHO one of the most interesting is the Large Angle and Spectrometric Coronagraph (LASCO), which studies the Sun's corona by creating an artificial solar eclipse. The LASCO instrument has been largely responsible for inadvertently discovering many comets near the Sun, with over 1,800 found to date.

SOHO has three primary objectives that it has been carrying out since its launch. One of these was to investigate the outer regions of the Sun, specifically the corona.

At the moment it is still unknown why the corona is hotter than the photosphere and chromosphere of the Sun, so it is hoped that SOHO might help to provide the answer in the future. SOHO has also been used to observe the solar wind, and also to study the interior structure of the Sun through a process known as helioseismology.



On the scale of solar flares, X-class storms are most powerful. SOHO took this image on November 2003 showing the most powerful ever recorded, which reached X28

## Take a tour of SOHO

SOHO is made up of two modules.

The Service Module forms the lower portion, while the Payload Module sits above

### Payload Module

This sits on top of the Service Module and houses all 12 of the instruments on board the spacecraft

### Service Module

The Service Module provides power, telecommunications, thermal control and direction to the spacecraft

### Malfunction

In 1998 SOHO suffered a major malfunction that almost rendered it unusable.

However, some smart thinking enabled scientists to regain control of the telescope, although it now operates without the help of its gyroscopes, the only three-axis stabilised spacecraft to do so

## Mission Profile

Solar and Heliospheric Observatory (SOHO)

**Mission dates:** 02/12/95-12/12/14

**Details:** SOHO is a joint project between the ESA and NASA. It was designed to study the origin of the solar wind, the outer atmosphere of the Sun and its internal structure. SOHO has found over 1,800 comets to date and discovered that quakes on the Sun's surface are caused by solar flares. It has also made the most detailed map of features on the solar surface.

### Antennas

SOHO transfers data back to Earth at a rate of between 40Kbits/s and 200Kbits/s using its high and low gain antennas

### Solar panels

SOHO's only source of energy is from the Sun, but as it is in orbit around it, it has a large supply of energy

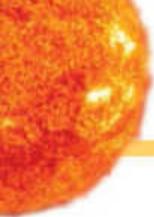
### LASCO

SOHO's Large Angle and Spectrometric Coronagraph (LASCO) produces detailed imagery of the solar corona by creating an artificial eclipse



The SOHO spacecraft has survived 17 years in space, 15 more than its initial mission length

**"SOHO is located near to Lagrangian 1, which is a point between the Earth and the Sun about 1.5 million km (930,000 mi) from our planet"**



# Observing the Sun

Humanity has been fascinated by the Sun for thousands of years and even primitive records still prove useful. Discover more about the past, present and future of studying the Sun

Observations of the Sun have been used for both scientific and religious observations for millennia. Civilisations have used the Sun to keep an accurate count of days, months and years since at least 300BC, while scientists such as Galileo studied the Sun through telescopes to discern some of its characteristics.

At the Chankillo archaeological site in Peru can be found the oldest solar observatory in the Americas, a group of 2,300-year-old structures used to track the motion of the Sun known as the Thirteen Towers. These towers provide a rudimentary solar calendar through which the Sun can be traced.

The towers, each between 75 and 125 square metres (807 and 1,345 square feet) in size, run from north to west along a ridge along a low hill. From an observation point to the west of the ridge the Sun can be seen to rise and set at different points along the ridge, which allowed ancient civilisations to track the number of days it takes the Sun to move from tower to tower.

Much later, in 1612, the renowned Italian astronomer Galileo Galilei (1564-1642) used his telescope to make one of the first observations of sunspots on the surface of the Sun. In 1749 daily observations began at the Zurich Observatory and, since 1849, continuous observations have been made to count the number of sunspots

present on the Sun's surface at any one time.

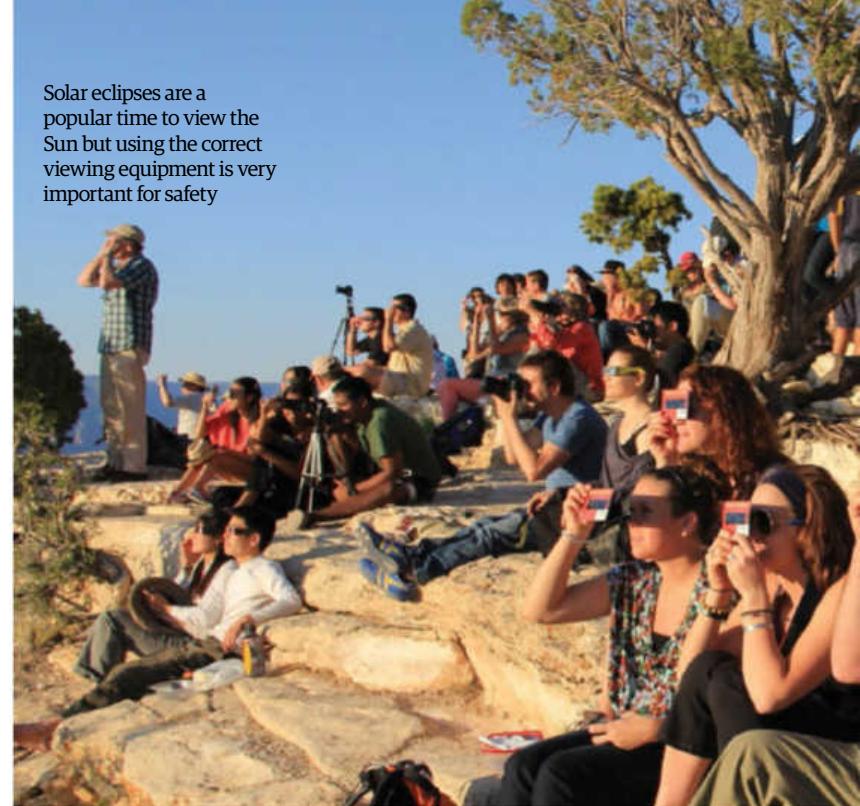
Fast forward to today and, aside from SOHO, one of the primary telescopes used to observe the Sun is the Japanese Hinode spacecraft. Hinode is a telescope in sun-synchronous Earth orbit, which allows for nearly continuous observation of the Sun. It was launched on 22 September 2006 and was initially planned as a three-mission study of the magnetic fields of the Sun, but its mission has since been extended as it continues to operate nominally.

Another important Sun-observing telescope is the Solar Dynamics Observatory (SDO), launched by NASA in 2010. The goal of the SDO is to study the influence of the Sun near Earth, predominantly how the Sun's magnetic field is responsible for the solar wind once it is released into the heliosphere. It should help scientists further understand the Sun's influence on the Solar System.

In the future, NASA's Solar Probe Plus will be the closest spacecraft to



Solar eclipses are a popular time to view the Sun but using the correct viewing equipment is very important for safety



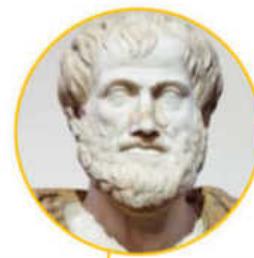
the Sun, approaching to within just 8.5 solar radii (5.9 million km, 3.67 million mi) after its launch in 2018. It will probe the outer corona of the Sun in unprecedented detail, while becoming the fastest spacecraft of all time in the process, at up to 200 kilometres per second (120 miles per second).

Apart from million dollar telescopes, many amateur astronomers around the globe today observe the Sun either for entertainment or educational benefit. Using specially designed glasses, people can look at the Sun from Earth, although caution must be taken to limit time spent looking at the Sun and it should never be looked at with the naked eye. Other methods of solar observation include using a

telescope to produce a trace of the Sun, a method similar to that used by Aristotle and his camera obscura in the 4th Century BC. Again, precautions must be taken here, as under no circumstances should the Sun be directly observed through a telescope.

Whatever the method, and whatever the mission, observations of the Sun have been a long tradition and will continue to be so for the foreseeable future. Astronomical events such as planetary transits and solar eclipses provide amateur astronomers with opportunities to see extraordinary solar phenomena, while agencies throughout the world will continue to study the Sun and learn more about how the fantastic star works. ●

**"Civilisations have used the Sun to keep an accurate count of days, months and years since at least 300BC"**



400BC

The world's oldest solar observatory, the Thirteen Towers of Chankillo, is built in Peru to track the motion of the Sun.

350BC

Aristotle uses a camera obscura to project an image of the Sun and observe a partial eclipse.

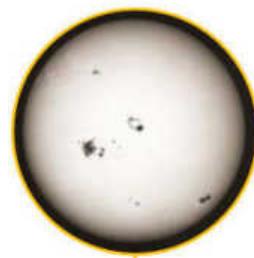
1612

Galileo Galilei uses his telescope to make one of the first observations of sunspots on the surface of the Sun.

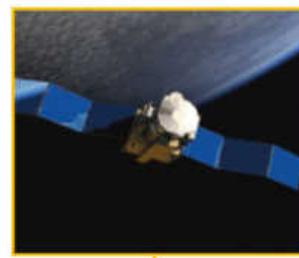
## The history of observing the Sun



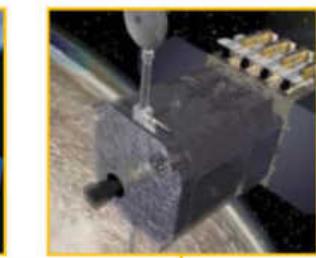
**1749**  
Daily observations of the Sun begin at the Zurich Observatory in Switzerland.



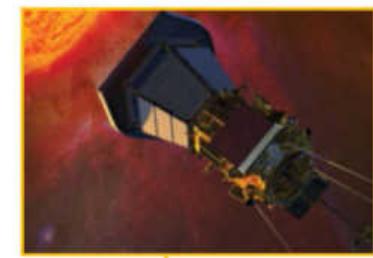
**1849**  
New observatories around the world allow continuous observations of sunspots to be made.



**2006**  
The Japanese telescope Hinode is launched to study the magnetic fields and atmosphere of the Sun.



**2010**  
NASA launches the Solar Dynamics Observatory, its primary goal being to study the influence of the Sun near Earth.



**2018**  
NASA's new Sun-observing telescope Solar Probe Plus will launch and become the closest spacecraft to the Sun.

## Different ways to observe the Sun

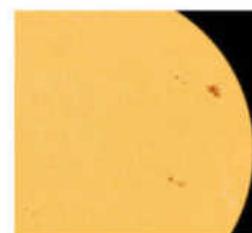
On Earth we perceive the Sun to be a yellow ball of gas in the sky but, like anything as hot as the Sun, it is actually closer to being white hot when viewed from space. There are several telescopes currently observing the Sun but

the large majority of our images come from the STEREO telescope and the SOHO observatory, both in orbit around the Sun. By viewing the Sun in different wavelengths we can study its different characteristics and see some of its main features in a different light.



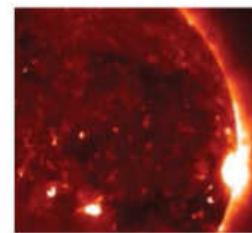
### Ultraviolet

Images of the Sun in ultraviolet light are between wavelengths of about 19.5 and 30.4 nanometres. Such an image of the Sun is at the lower end of this scale, and allows us to see where the lower part of the corona and upper part of the chromosphere combine. The light in this image comes from active regions in the Sun's chromosphere.



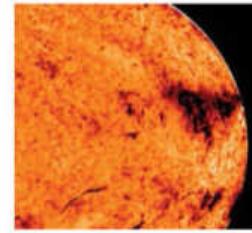
### Visible

Visible light images commonly refer to those viewing the Sun in white light, which shows the true colour of the white-hot Sun. In visible light images we can see the Sun's photosphere, which is about 6,000 degrees Celsius (10,832 degree Fahrenheit) and therefore appears white-hot. Here, we can see dark spots on the surface of the Sun, known as sunspots.



### X-ray

Light with a wavelength shorter than ten nanometres (ten billionths of a metre) is known as X-ray light. X-rays are emitted from the Sun's corona, the hottest visible layer of the Sun's atmosphere. The visible areas of brightness are places where more X-rays are being emitted, around areas of increased activity on the Sun's surface.



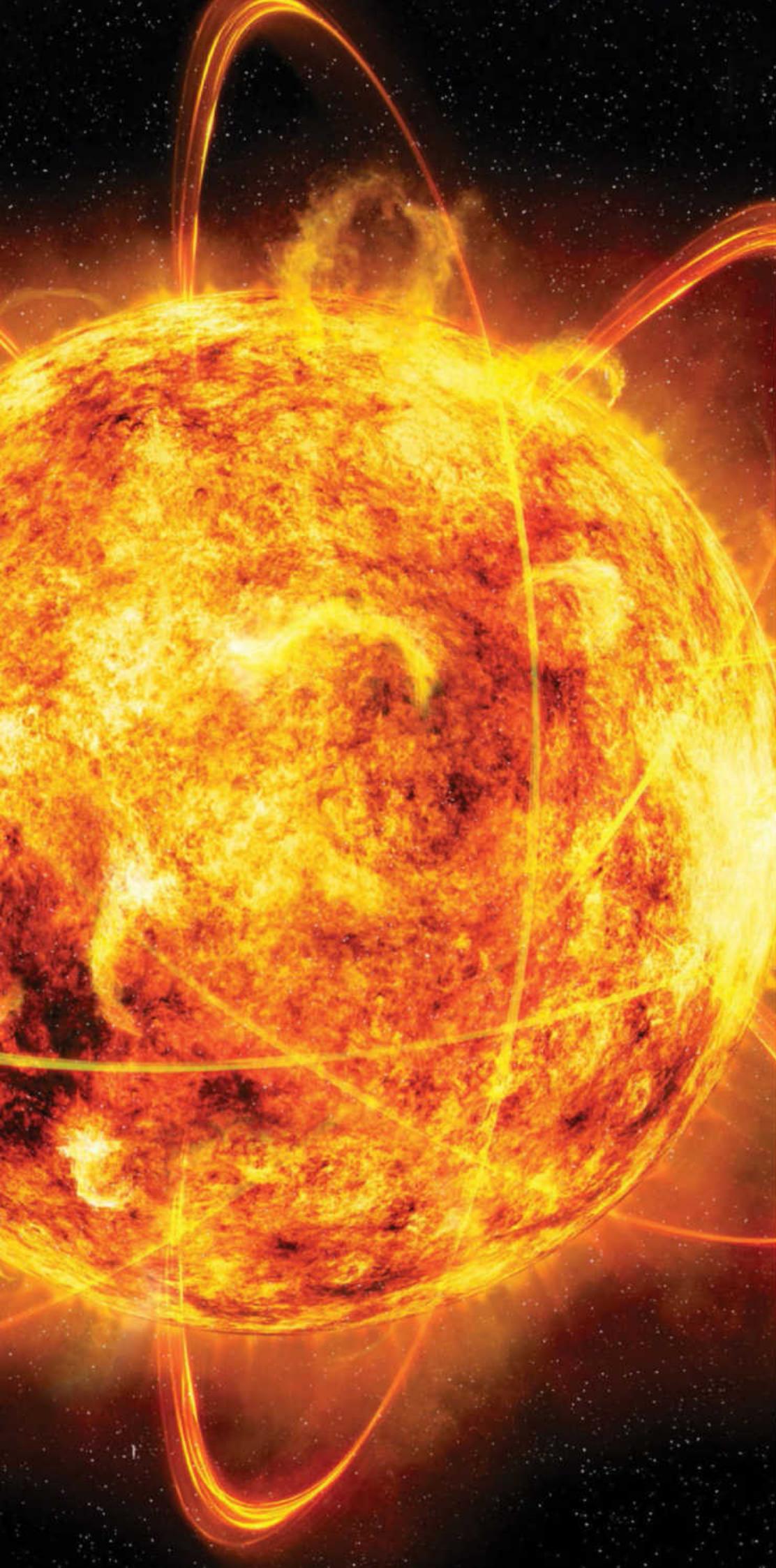
### Infrared

Infrared light is responsible for more than half of the Sun's power output, typically around wavelengths of 1,080 nanometres. Infrared images show features of the Sun's chromosphere and corona. The dark features on the image are areas where the gas is more dense, absorbing more infrared light than in other areas.

# FUSION POWER SUN



Our local star pumps out vast amounts of heat and light, which supports all life on Earth. But where does it come from, and just what happens to it on its journey through the Sun?



The Sun is a huge ball of blazing gas, with a visible surface roughly 1.4 million kilometres (870,000 miles) across. In a single second it pumps out energy equivalent to what could be generated by 2 billion large Earth power stations in a year, making use of a process that scientists have only been able to harness for a fraction of a second in Earth-based laboratories: nuclear fusion.

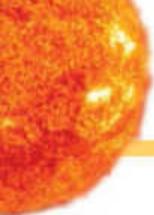
Fusion is the process of joining together the atomic nuclei of light elements to build the nuclei of heavier ones. All atoms consist of a nucleus (a tiny, positively charged core that accounts for the vast majority of their mass) surrounded by a cloud of orbiting electrons (lightweight, negatively charged particles). In comparison to the entire atom, the nucleus is about the size of a pea inside an electron cloud the size of a football stadium. In the extreme conditions of the Sun's interior, atoms break apart into their component electron and nuclei, allowing matter to reach extreme densities (about 150 times the density of water). Heated to temperatures of around 15 million degrees Celsius (27 million degrees Fahrenheit) in the core of the Sun, atomic nuclei are slammed together at high speed - and the changes they go through in order to remain stable release the energy that allows the Sun to shine.

A century ago, the source of the Sun's power was one of the biggest questions in astronomy. Geological and fossil discoveries had shown that the Earth was hundreds of millions, if not billions, of years old. But popular models of the Sun's power source, such as the idea that it generated energy by slow gravitational contraction, suggested that it could only sustain Sun-like levels of energy for a few tens of millions of years.

Clues to a solution came from a number of different directions. Spectroscopy (the analysis of light from the Sun and other objects to identify the chemical fingerprints of their constituents) had revealed that our star and most others are dominated by the two lightest and most abundant elements in the universe - hydrogen and helium. Most astronomers agreed that the Sun and planets had formed by collapsing out of a cloud of interstellar gas (mostly hydrogen) and dust similar to some of the nebulae they saw through their telescopes, and it seemed clear that stars had to become dense and hot in the first place in order to start shining. At around the same time, physicists and chemists were discovering the secrets of atomic structure for the first time, and precise measurements of atomic masses showed that a single atom of helium contained almost four times the mass of four individual hydrogen atoms.

Then, in 1920, British astrophysicist Arthur Stanley Eddington put forward an ingenious idea - what if the Sun generated its energy by combining lightweight hydrogen nuclei to make helium? If four hydrogen nuclei fuse to form a single helium nucleus, there will be a small but significant amount of mass (roughly 0.7 per cent) 'left over', and Eddington suggested this might be converted directly into a relatively large amount of energy according to Einstein's famous equation  $E=mc^2$ .

Today we know this is exactly what happens at the centre of stars like the Sun - 620 million tons of hydrogen nuclei are fused into helium every



# The Sun

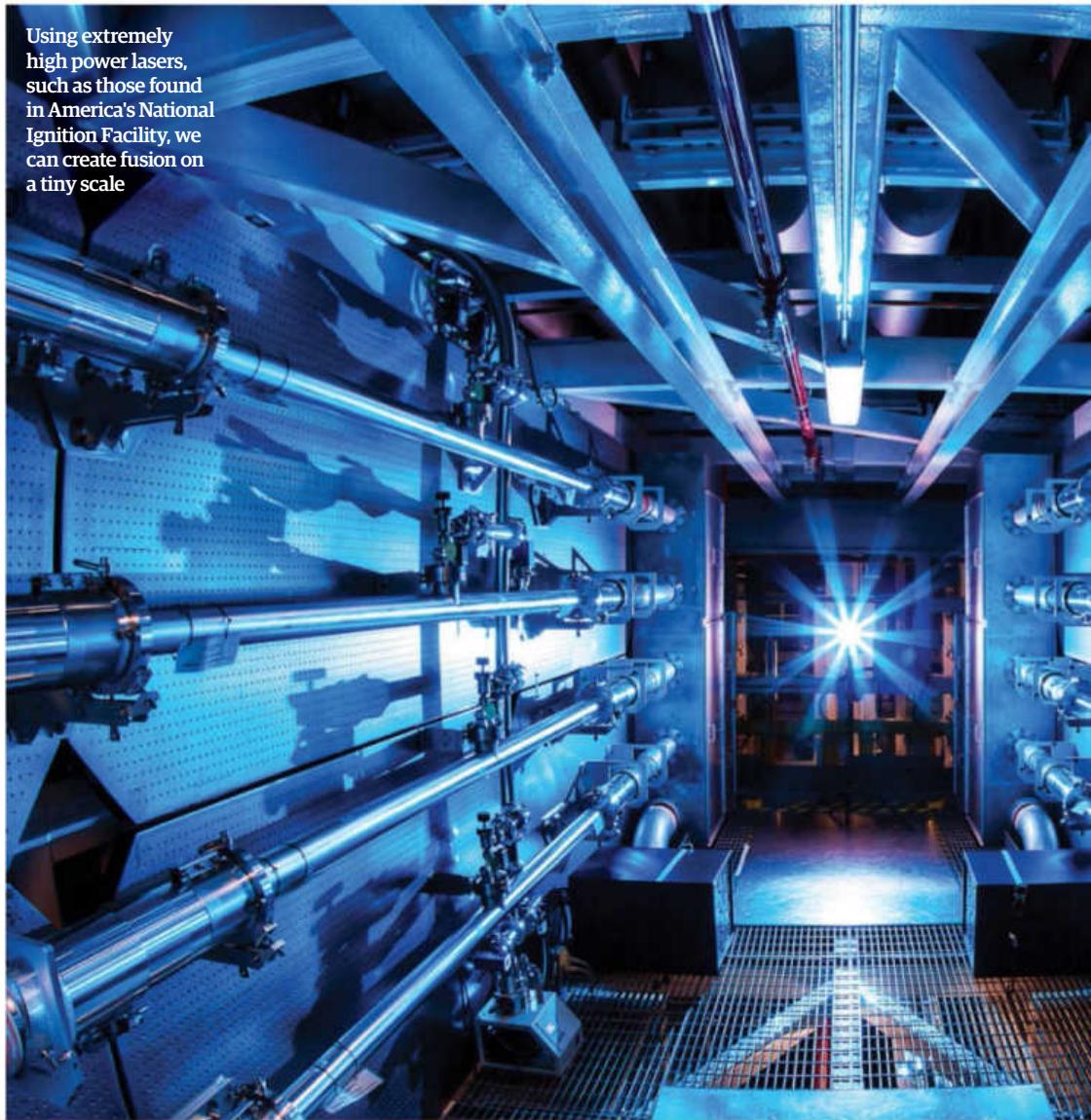
second. However, it took decades, and many further discoveries about the nature of the nucleus, before astrophysicists could describe what happens in detail.

Nuclear fusion in the Sun takes place mostly through a process known as the proton-proton (p-p) chain. Today we know that atomic nuclei consist of two distinct particles - positively charged protons and uncharged neutrons - with identical masses. The number of protons dictates the number of electrons required to balance them, and therefore the atom's chemical properties and which element it forms. Neutrons, meanwhile, provide additional mass and stability, forming variant atoms of the same element with the same chemistry but different mass. These are known as isotopes.

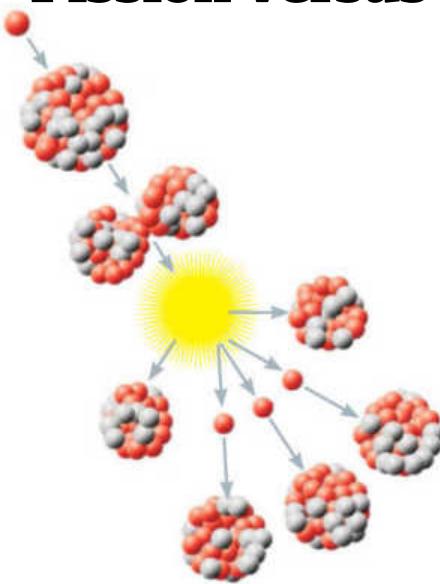
Hydrogen usually consists of atoms with just a single lone proton orbited by a single electron. In the extreme conditions of a stellar interior, however, these atoms are ionised, with their electrons stripped away to expose the bare nucleus. A helium nucleus, in contrast, contains two protons and two stabilising neutrons - so where do the neutrons come from? It seems that during the fusion process, protons are able to spontaneously transform into neutrons through a process known as beta-plus decay. The proton effectively 'sheds' its positive charge by emitting a positron (the positively charged equivalent of an electron) and an almost-massless particle known as a neutrino. P-p chain fusion actually involves several distinct pathways and each of its steps releases energy, while any positrons that may have been liberated along the way soon collide with electrons and disappear in another burst of energy known as annihilation.

At relatively large scales (those of whole atoms), we might expect repulsion due to the familiar electromagnetic force to push positively charged protons away from each other. However, given enough temperature, speed and pressure, the protons

Using extremely high power lasers, such as those found in America's National Ignition Facility, we can create fusion on a tiny scale

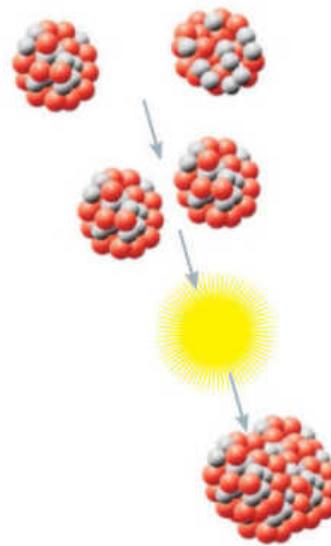


## Fission versus Fusion



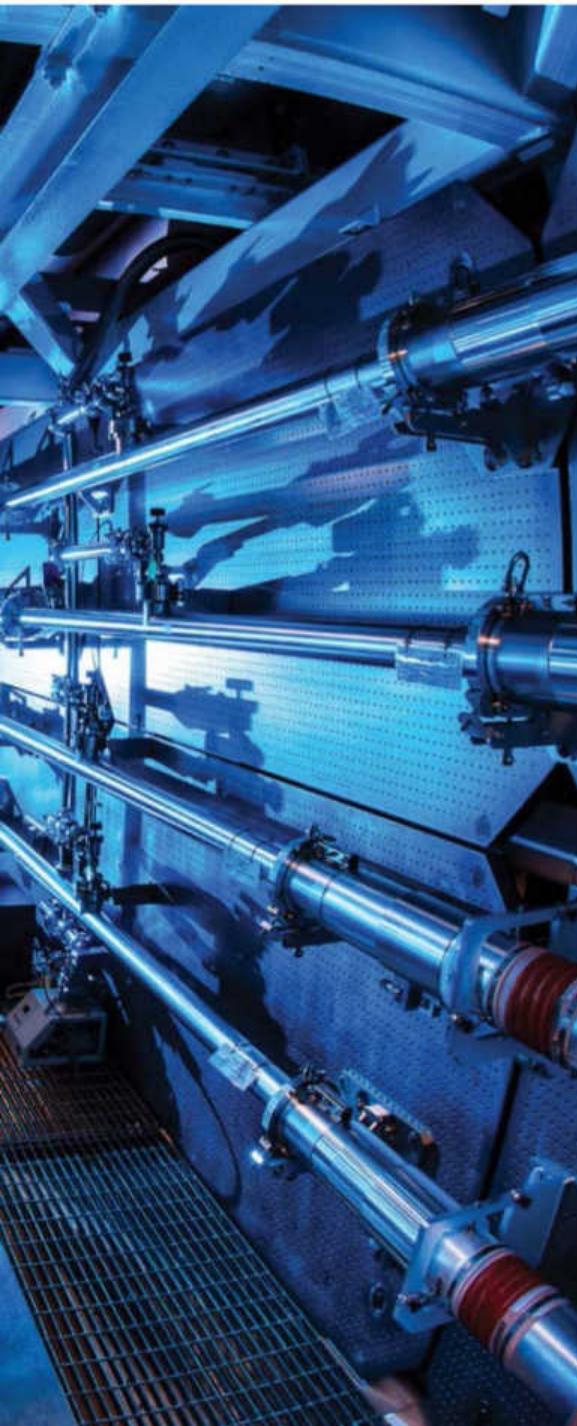
### Fission

Nuclear fission is the most familiar form of nuclear reaction here on Earth, but it is very different from fusion. Fission involves the release of energy from the splitting apart of a heavy atomic nucleus whose configuration of protons and neutrons have left it unstable or 'radioactive' - it produces one or more lighter nuclei along with other subatomic particles or excess energy. Fission happens regularly in nature, but can also be triggered artificially, which is the principle behind nuclear power stations and, unfortunately, atomic bombs as well.



### Fusion

Unlike fission, fusion is very unfamiliar to us on Earth - it only happens naturally in the extreme conditions of stars, although scientists can replicate it in experiments. Fusion is the forging together of lighter atomic nuclei to make heavier ones and release energy - in the Sun, this mostly involves fusing hydrogen to make helium but in other stars it's possible to fuse elements up to and including iron (elements beyond this absorb energy in the process). Harnessing nuclear fusion remains a dream at the moment, but it offers a potentially limitless source of clean energy.

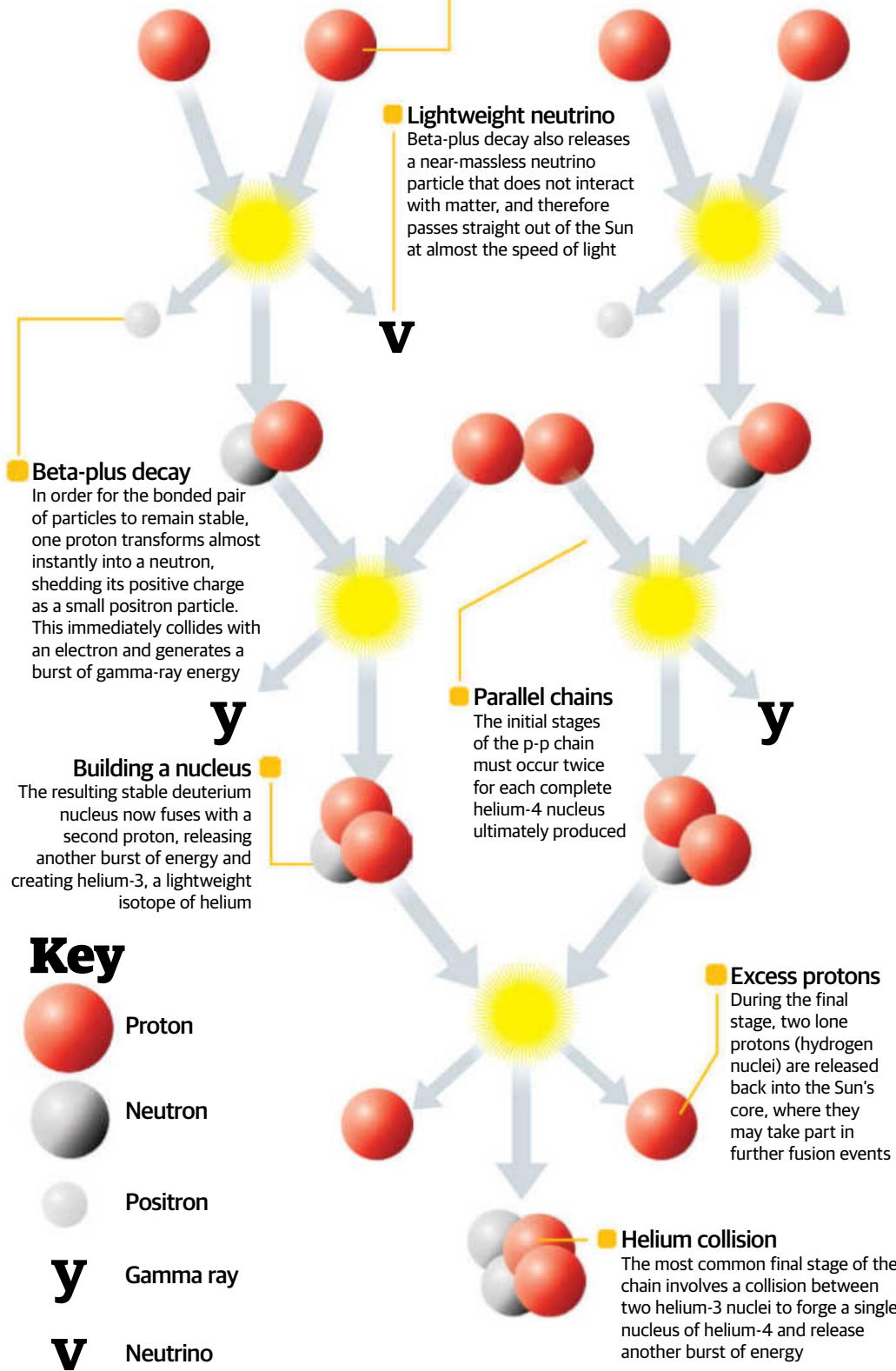


"Life on Earth could not have come into being without nuclear fusion in the Sun: we could not survive without it"

## Proton-proton chain fusion

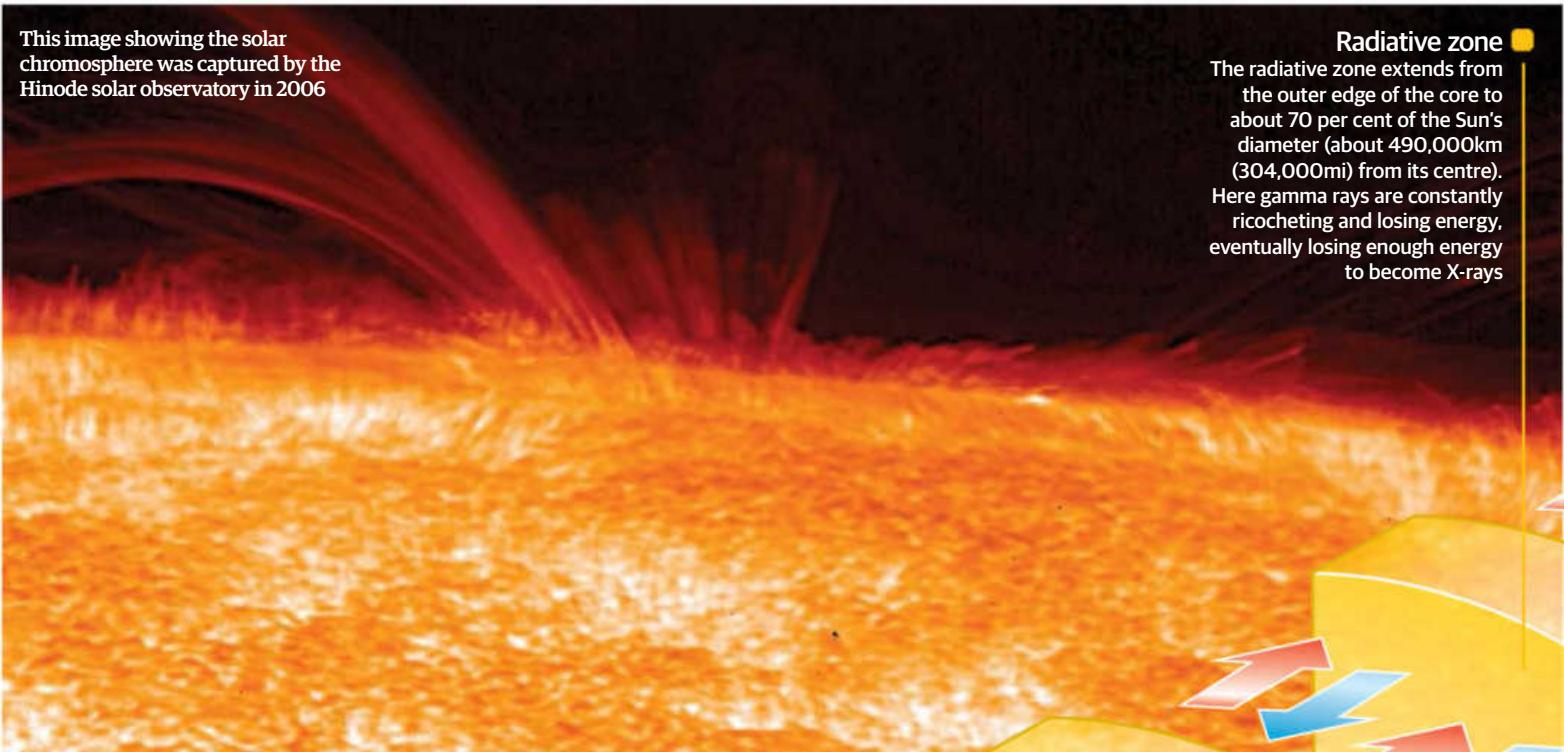
P-p chain fusion actually involves several distinct pathways, but the early steps always involve the fusing of two protons to form a highly unstable isotope called helium-2.

**Colliding protons**  
Stripped of their electrons in the heart of the Sun, exposed hydrogen nuclei are simply individual positively charged protons. At intense temperatures and pressures, they are forced together, overcoming forces of electromagnetic repulsion



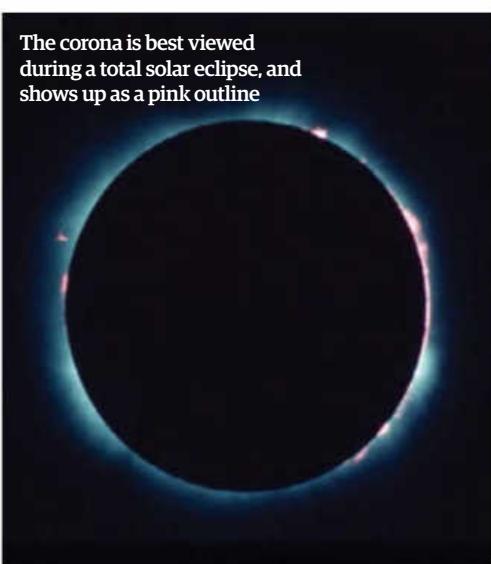
# The Sun

This image showing the solar chromosphere was captured by the Hinode solar observatory in 2006



**Radiative zone** ■  
The radiative zone extends from the outer edge of the core to about 70 per cent of the Sun's diameter (about 490,000km (304,000mi) from its centre). Here gamma rays are constantly ricocheting and losing energy, eventually losing enough energy to become X-rays

The corona is best viewed during a total solar eclipse, and shows up as a pink outline



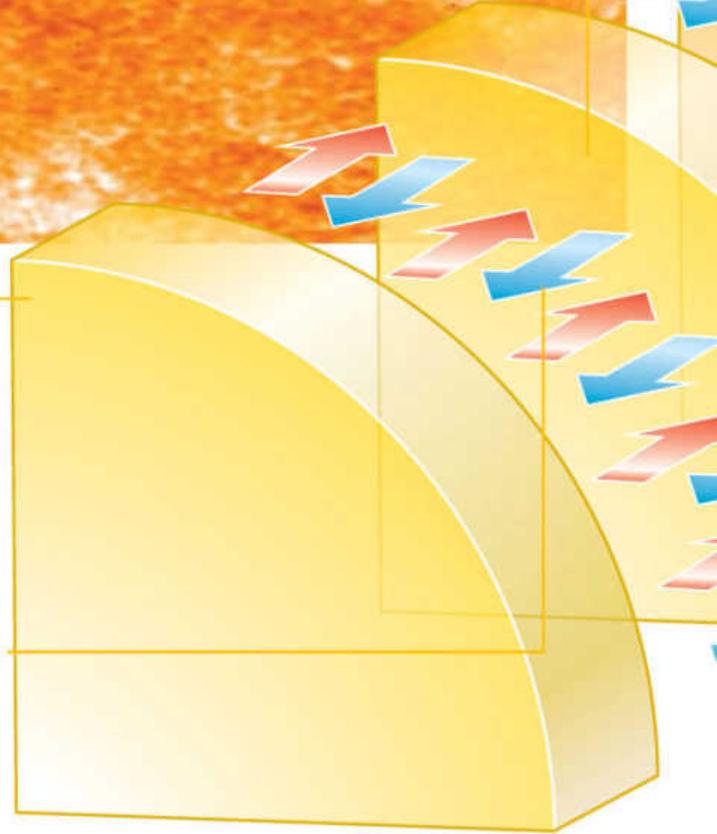
## Inner core

The Sun's core, where fusion can be sustained, takes up about 20 per cent of its diameter (roughly 22 times the width of Earth).

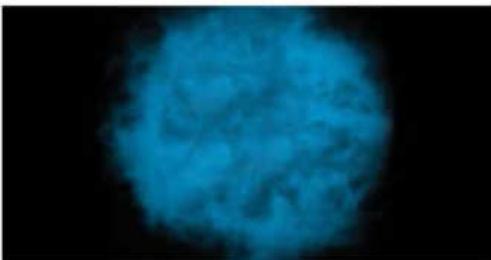
High temperatures and pressures allow hydrogen nuclei (protons) to fuse together, building into helium nuclei and releasing energy in the process

## Hydrostatic equilibrium

At every point within the Sun's overall structure, the outward pressure from radiation and the inward pull of gravity must be precisely balanced to prevent material being dragged inwards or blown away



## How did our Sun form?



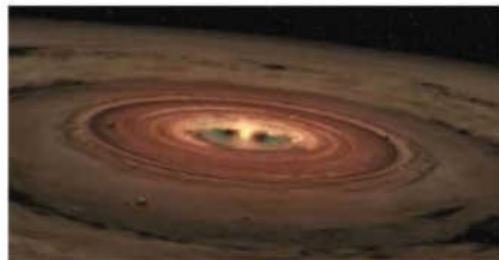
### 1. Origins of a star

Our Sun and its planets were born when a hydrogen-rich cloud of interstellar gas and dust began to slowly collapse around 5 billion years ago.



### 2. Flattening out

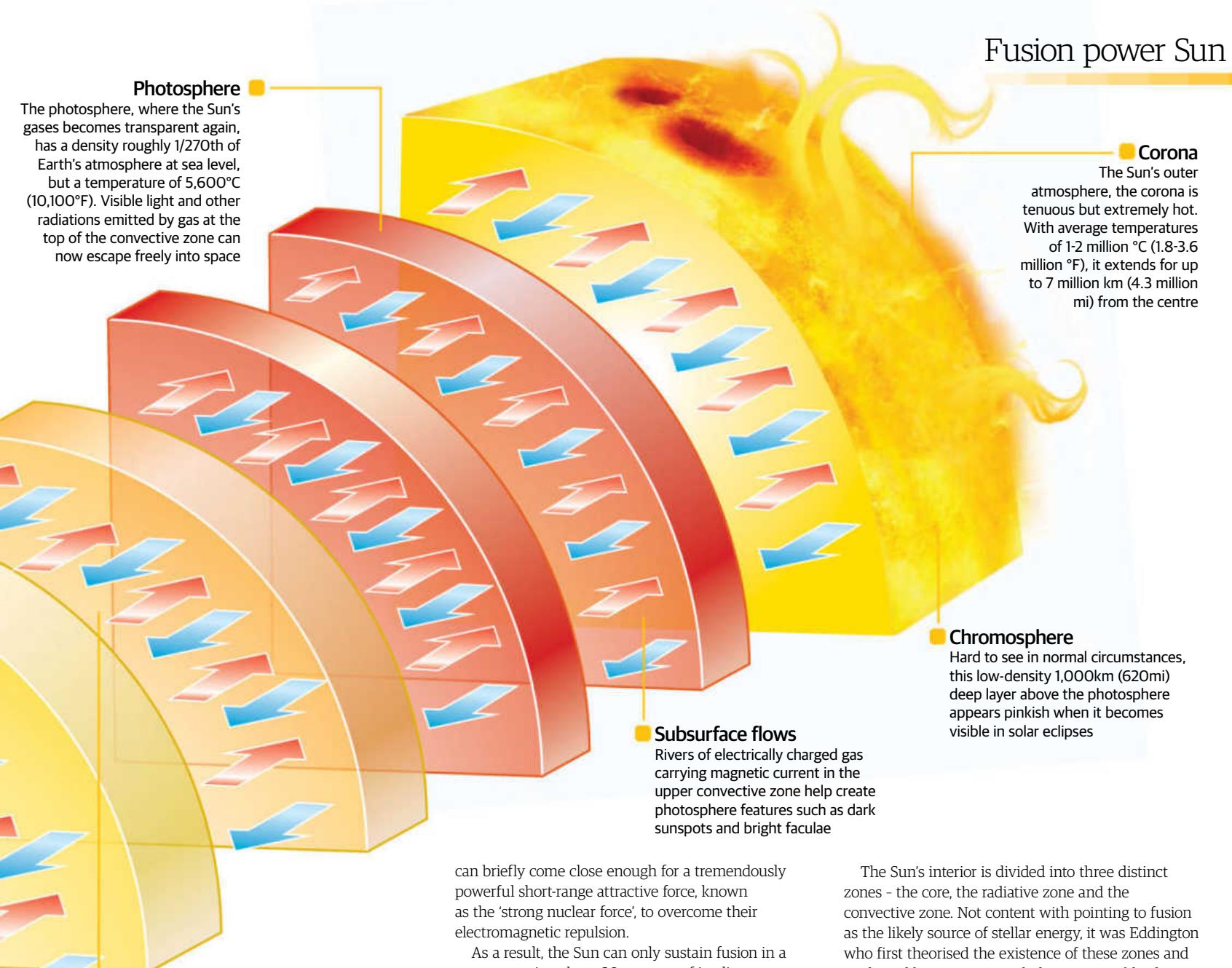
As the cloud grew denser, it spun faster. Collisions within the cloud tended to even out its rotation, resulting in a flattened disc with a large central bulge.



### 3. Condensing Sun

As the central region of the 'protostellar nebula' grew more massive, its gravity began to pull in more material, gradually condensing and heating up.

# Fusion power Sun



## Convective zone

The opaque convective zone stretches from the top of the radiative zone out to the Sun's visible radius of 696,000km (432,000mi), where it becomes transparent at the photosphere. Here, energy is transported through rising currents of hot gas, rather than as radiation

can briefly come close enough for a tremendously powerful short-range attractive force, known as the 'strong nuclear force', to overcome their electromagnetic repulsion.

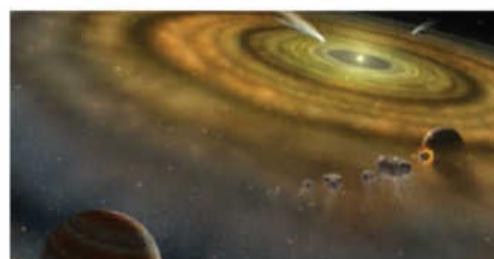
As a result, the Sun can only sustain fusion in a core occupying about 20 per cent of its diameter. Power released here takes the form of gamma rays - electromagnetic waves similar to the light but with much shorter wavelengths and higher frequencies that allow them to carry much more energy. These rays still have a long journey ahead of them to reach the Sun's visible surface and escape into open space.

The Sun's interior is divided into three distinct zones - the core, the radiative zone and the convective zone. Not content with pointing to fusion as the likely source of stellar energy, it was Eddington who first theorised the existence of these zones and explained how stars as a whole remain stable, despite the firestorm raging within them. This is thanks to a balancing act called hydrostatic equilibrium: the forces acting on any arbitrary layer within the star, he showed, are always precisely balanced between outward pressure from radiation flooding away from the core, and the inward pull of gravity.



## 4. Protostar

At first, the Sun shone by radiating energy generated by its own gravitational contraction. It was a large, warm ball of gas surrounded by a ring of debris.



## 5. Ignition!

The Sun continued to grow smaller and denser, until its core became hot enough to begin nuclear fusion. Meanwhile the debris around it formed into planets.



## 6. The Solar System today

The Sun is roughly halfway through an estimated 10 billion year lifetime during which it will continue to shine by fusing hydrogen into helium in its core.

# The Sun

As its name suggests, the radiative zone is the region where energy is transferred mainly through radiation (the same is true of the core itself). The sea of particles is so tightly packed that gamma rays can travel for only a very short distance before interacting with something (usually a fast-moving 'free electron'). Each interaction 'scatters' the gamma ray, transferring a little of its energy to the particle and therefore helping to retain the heat of the central regions. Each scattering event sends the gamma ray off in a new direction, and as the gamma rays ricochet from one particle to the next, they follow a long and complicated path known as a 'random walk'.

It might seem as though the gamma rays would be perpetually trapped in the central region, but the very gradual fall-off in density of material from the centre of the Sun outwards ensures that rays are more likely to travel slightly longer distances before scattering, if they move in directions that are away from the centre. Therefore, over countless interactions, the gamma rays gradually lose energy and move into the Sun's less dense upper layers.

According to the latest models, radiation takes about 170,000 years to travel through the core and radiative zones, moving at an average speed of just 2.9 kilometres (1.8 miles) per year. By the time they reach the upper edge of the radiative zone, 70 per cent of the way to the Sun's surface, the surrounding

temperatures have dropped to about 1.5 million degrees Celsius (2.7 million degrees Fahrenheit) and the wavelength of the rays has lengthened considerably - they are now mostly X-rays rather than gamma rays.

Here, at the bottom of the Sun's convective zone, conditions change rapidly from those below. The Sun's materials become more opaque, but also develop a greater ability to absorb heat energy, so radiation ceases to be the most efficient means of transferring energy outwards. Instead, convection (the bulk movement of heated matter) takes over. X-rays heat gas at the bottom of a layer more than 200,000 kilometres (124,000 miles) deep, and as this gas heats and expands, it rises up through overlying cooler gas, taking about ten days to complete the final leg of its journey towards the Sun's surface.

Almost 700,000 kilometres (435,000 miles) from its centre, the Sun's composition changes dramatically once again. As temperatures drop to around 5,600 degrees Celsius (10,100 degrees Fahrenheit), light-absorbing ions that are common in the convective zone disappear, leaving most of the gas in a pure atomic form that is transparent to visible light. Radiation once again becomes the most efficient means for energy to escape, and so electromagnetic rays emitted by the searing gas are no longer reabsorbed and can escape into space.

## The future for solar fusion

As hydrogen is slowly replaced by helium in the centre of the Sun, the core will grow denser and hotter, and the rate of fusion will increase in response. This causes the Sun to brighten gradually over time - by about one per cent every 110 million years. Once the core hydrogen is exhausted, more radical changes will take place. At first, hydrogen fusion will move out into a shell around the core and the Sun will swell into a red giant. Later, the core will grow dense enough to fuse helium for a brief phase before swelling again and shedding its outer layers in a planetary nebula.

### 1. Late main sequence

**Core temperature:** 20 million °C

**Primary nuclear reaction:** Hydrogen → Helium in core

**Elements formed:** Helium

### 4. Asymptotic Red giant

**Core temperature:** 200 million °C

**Primary nuclear reaction:**

Helium → Carbon in inner shell,  
Hydrogen → Helium in outer shell

**Elements formed:** Helium, Carbon, Nitrogen, Oxygen

### 3. Helium Burn

**Core temperature:** 100 million °C

**Primary nuclear reaction:** Helium → Carbon in core, Hydrogen → Helium in shell

**Elements formed:**

Helium, Carbon, Nitrogen, Oxygen

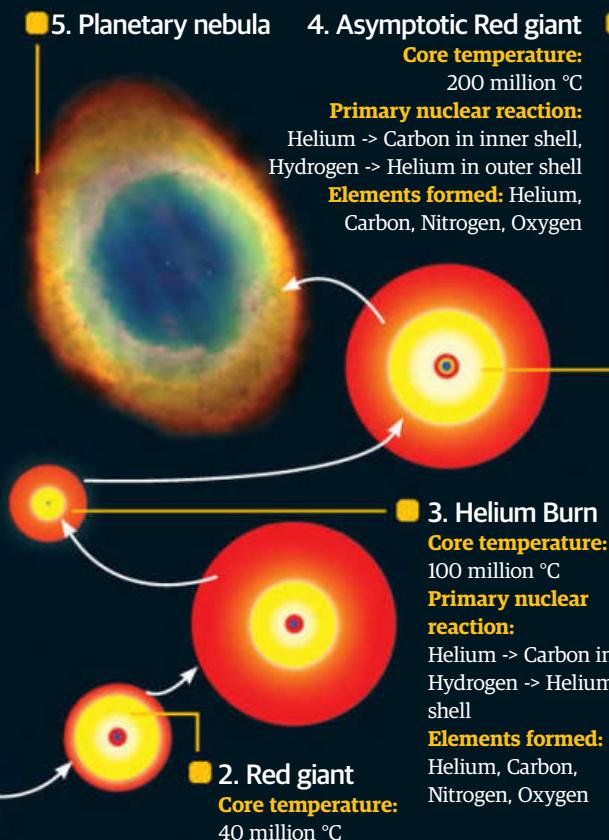
### 2. Red giant

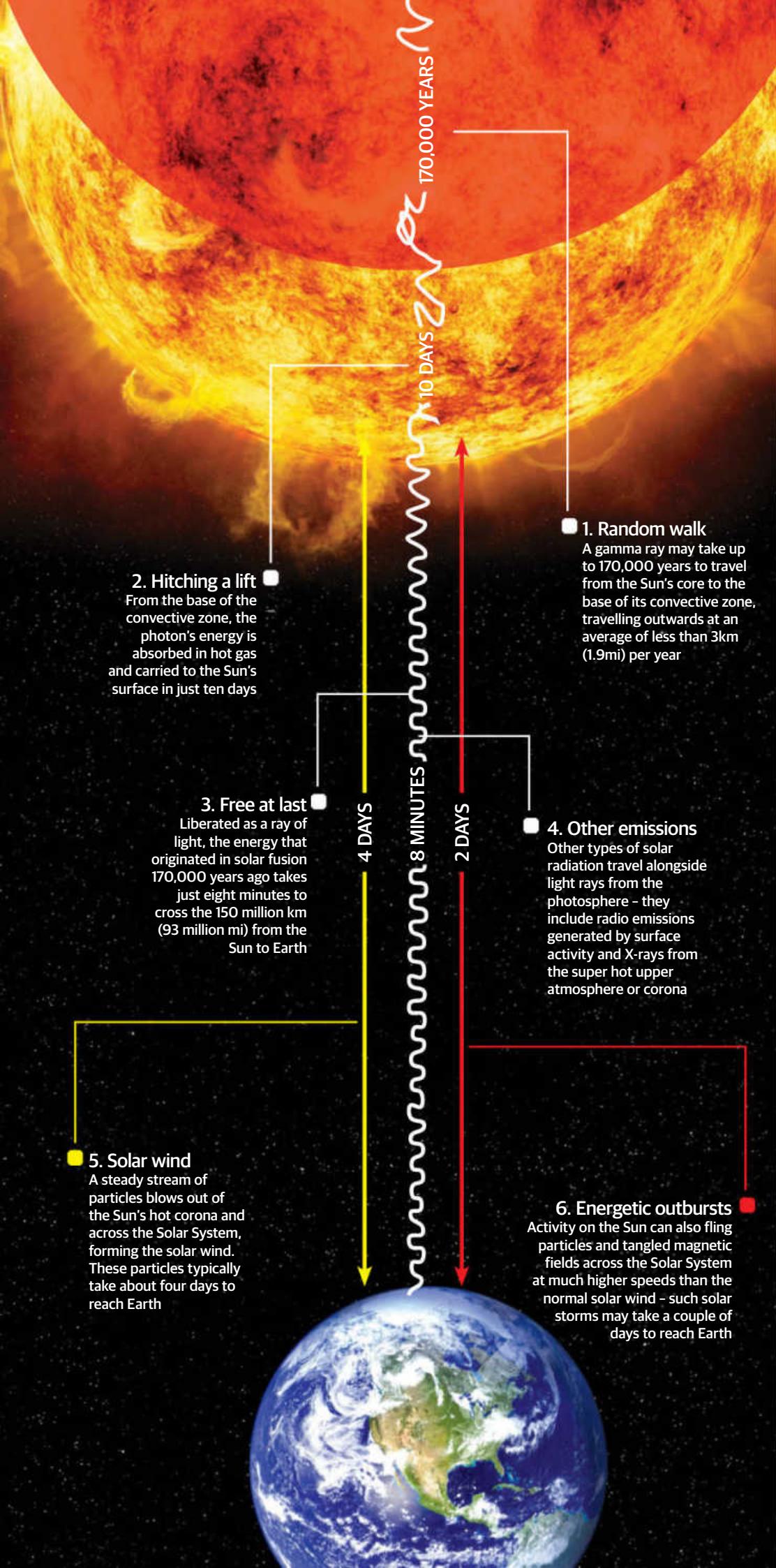
**Core temperature:** 40 million °C

**Primary nuclear reaction:**

Hydrogen → Helium in shell around core

**Elements formed:** Helium





This transition region between the opaque inner Sun and its transparent upper atmosphere can be a few hundred kilometres deep and, if viewed close up, would resemble the gradual clearing of an incandescent fog. However, on the scale of the Sun as a whole, the boundary is very thin, and so the Sun appears to have a sharply defined outer surface called the photosphere.

Thanks to the relatively low temperature of the Sun's surface, it releases a mixture of different radiations - ultraviolet rays, visible light and infrared (heat) radiation. These might be comparatively feeble compared to the original gamma rays generated in the core, but the energy they have lost along the way has helped to sustain the Sun's internal power plant.

The Sun's surface and upper atmosphere are the only parts of our star that we can observe directly, but they reveal a great deal about the processes going on within. Viewed through a filter that blocks out most of its blazing light, the photosphere is alive with a seething, shifting pattern of bright, dark-edged spots known as granulation. Each granule marks a single convection cell - the bright spot is formed where rising hot gas radiates its energy away into space, while the dark rim is formed of cooling gas sinking back down towards the interior. Individual granules are a relatively short-lived phenomenon of the upper convection zone - perhaps 1,500 kilometres (932 miles) across and with lifespans of just 15 minutes. However they're supported on deeper and larger 'supergranules', up to 30,000 kilometres (18,000 miles) wide and with lifespans of up to a day.

In addition to these fairly placid, ongoing processes, the photosphere (together with a thin overlying layer called the chromosphere) also develops a variety of more dramatic, intermittent features such as dark sunspots, bright faculae and looping arcs of gas known as prominences. Such features are linked to changes to a solar magnetic field generated within the churning convective zone. These come and go with the waxing and waning of the 11-year solar cycle and are linked to more violent events such as solar flares.

According to most calculations, nuclear fusion should supply enough energy to keep the Sun shining for about 10 billion years before the supplies of fuel in its core are exhausted. So given that the Solar System formed some 4.5 billion years ago, we're about halfway through the Sun's hydrogen-burning lifetime. As the hydrogen starts to run out, physical changes to the structure of our local star will enable it to keep shining for perhaps 2 billion years more, but they will have a profound influence on the entire Solar System and certainly leave Earth uninhabitable long before then.

Today, however, our planet bask in the energy generated by a nuclear furnace 150 million kilometres (93 million miles) away. Happily for us, the radiation the Sun releases at its surface is a lot less damaging to living tissues than that generated in its core - thanks in large part to about 500,000 kilometres (310,000 miles) of shielding in the form of the radiative and convective zones. Life on Earth could not have come into being without nuclear fusion in the Sun, we could not survive without it - and perhaps one day we will even learn to harness it for our own purposes.

# The Sun

## HIP 56948

Like our Sun, HIP 56948 has a very low amount of lithium

## Solar System

Our Sun is the perfect size and composition to support life on Earth and perhaps elsewhere in the Solar System

"HIP 56948 has physical properties and a chemical composition identical to that of the Sun"

# The Sun's twin star

## The most Sun-like star that we know of could kick-start the search for extraterrestrial life in the universe

Since the dawn of mankind our Sun has been regarded as unique. In ancient times it was thought to be the only star in existence, responsible for determining the day and night cycles on Earth. In the modern era we know it to be the heart and soul of the Solar System but it has long been regarded as one-of-a-kind in its composition and size. Now, however, it appears that our Sun could just be one of many similar stars in the Milky Way alone, providing a key piece of evidence to the belief that life could be lurking elsewhere in the universe.

The Sun is about 4.6 billion years old, born from a cloud of hot dust and gas at the start of the Solar System. In that time it has dictated the motion and characteristics of every body in its vicinity, including providing our own Earth with the ability to support life. As astronomers began to discover and study more and more stars elsewhere in the universe, they noticed several key differences between the Sun and every other star that seemed to make our own just that little bit special.

First, every star they came across was either much larger or significantly smaller. Second was that most other stars were considerably older or younger. Third, and perhaps most important, was the puzzling discovery that our Sun contained a very low amount of lithium compared to other stars. If all stars were essentially created in the same manner, why did this level of lithium vary so much?

A reason for this was theorised in 2009 in a paper published in *Nature*. "The explanation of this puzzle is for us rather simple," said lead author and astrophysicist Garik Israelian. "The Sun lacks lithium because it has planets." Rather than close the case, however, Garik's proposal carried with it a much more pertinent question. If we could find a solar twin with a similar lithium content, would that be indicative of that star also having a similar planetary system to our own?

Astronomers began to search in earnest for such a solar twin, but to little avail. That was until a paper published in 2012 proclaimed to have not only found a star similar in size and age to our Sun, but also nearly identical in its composition. HIP 56948 is about 210 light years away in the Draco constellation. It has a radius 1.14 times that of our Sun, a mass slightly smaller and is almost identical in age, meaning it is at the same point in its stellar evolution. In the paper, entitled 'HIP 56948: A Solar Twin with a Low Lithium Abundance', authors Jorge Meléndez and Iván Ramírez said: "HIP 56948 has stellar parameters identical to solar within the observational uncertainties, being thus the best solar twin known to date. Considering the age of this star and its location and orbit around the galaxy, if terrestrial planets exist around it, they may have had enough time to develop life."

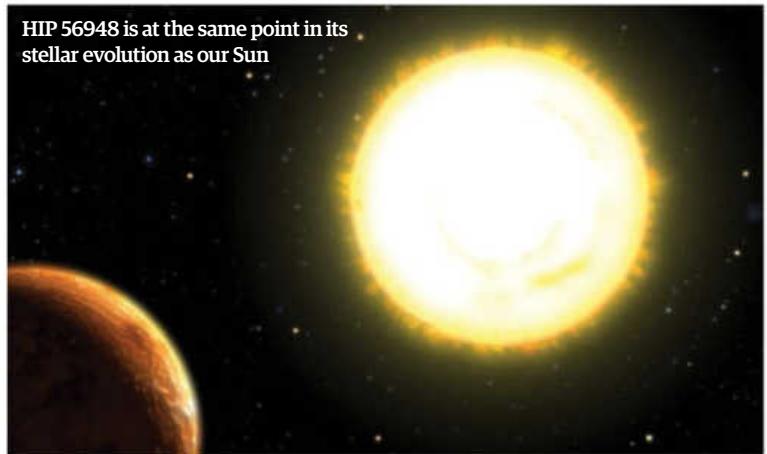
Of most interest, however, was the revelation that HIP 56948 shared

similar levels of lithium depletion as our own Sun, pointing to the presence of planets. However, there are no signs of large and hot Jupiter-like gas giant planets, suggesting that much smaller (and perhaps terrestrial) planets are in orbit. Finding such a star was a remarkable achievement, for our own Sun is regarded as one that has the optimal conditions around which such potentially habitable planets can form. Thus, in our continued search for life outside the Solar System, HIP 56948 represented a significant step forwards in the hunt for life-bearing exoplanets.

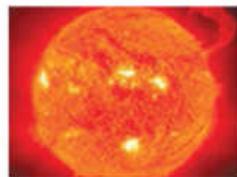
"HIP 56948 has physical properties and a chemical composition identical to that of the Sun, as well as a similar age," the paper continued. "Stellar ages are key in the search for complex life, especially if one considers that the formation timescale of complex life is similar to that for Earth. Furthermore, given its orbital properties, HIP 56948 is well within the galactic habitable zone. Considering these facts, HIP 56948 is an excellent candidate for life outside the Solar System."

In fact, the star is so Sun-like that Meléndez and Ramírez suggest it may completely change our understanding of how unique we are in the universe. "Besides the astrophysical significance of solar twins, there is another motivation to study them in detail: they help in answering the question of whether the Sun is unique or not, a question that has important philosophical consequences." Those consequences would be that there might be other places in the Milky Way, and the universe, where life such as ourselves could flourish. If the Sun were unique it would "suggest that our location in the universe is privileged for our existence as observers." The identification of HIP 56948, however, "can be used as an argument against [that theory]," and therefore allow us to theorise that there are many stars like our own Sun that have the necessary conditions around which life can form. Perhaps HIP 56948, our closest solar twin and a star not that far away in terms of astronomical distance, might just be one of those stars. ■

HIP 56948 is at the same point in its stellar evolution as our Sun



## The universe's Sun-like stars



**The Sun**

Radius: 696,000km  
Distance: 150 million km  
Surface temp: 5,778 K  
Age: 4.57 billion years



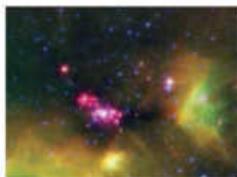
**HIP 56948**

Radius: 1.14 Suns  
Distance: 210 light years  
Surface temp: 5,748 K  
Age: 3.6 billion years



**18 Scorpii**

Radius: 1.01 Suns  
Distance: 45.3 light years  
Surface temp: 5,433 K  
Age: 4.7 billion years



**HD 143436**

Radius: Unknown  
Distance: 142 light years  
Surface temp: 5,768 K  
Age: 3.8 billion years



**HD 44594**

Radius: 1.0 Suns  
Distance: 82 light years  
Surface temp: 5,840 K  
Age: 4.1 billion years



**HD 98618**

Radius: 1.0 Suns  
Distance: 126 light years  
Surface temp: 5,843 K  
Age: 4.21 billion years

Our Sun and its potential solar twins

# The Earth & Moon

Understand more about our home planet and its only satellite

## **54 All about Earth**

Get under the surface of our home planet

## **66 Outpost Earth**

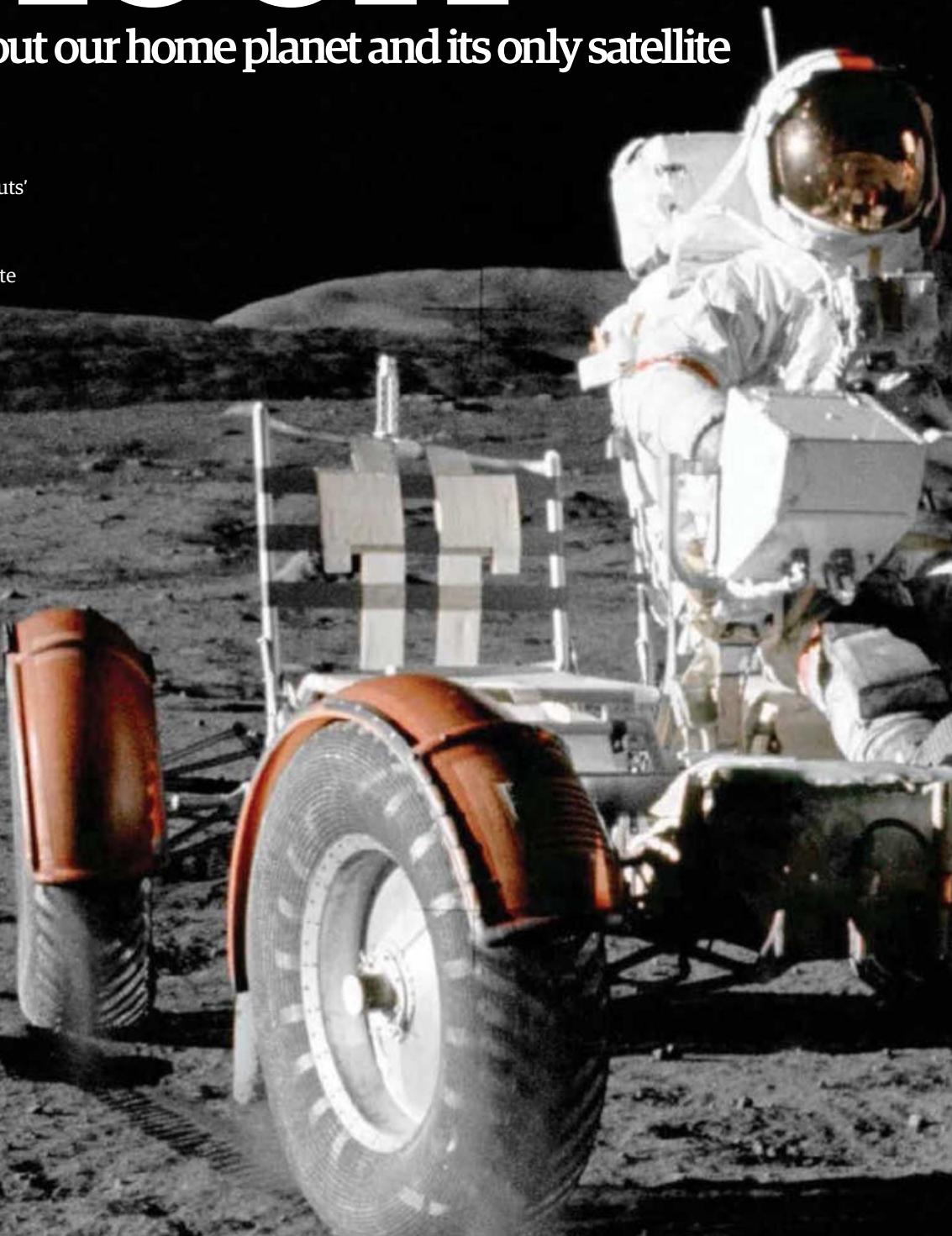
Discover how Earth is used as an astronauts' training ground

## **74 All about the Moon**

Explore the oddities of Earth's only satellite

## **86 Moon explorer's guide**

Learn about the landmarks of the Moon



**"The Moon is in synchronous rotation with the Earth - its rotation and orbital period are the same - so the same side is always facing Earth"**



# Earth & Moon



# All About... EARTH

When it comes to studying the planets of the Solar System we often overlook the Earth. However, as the only planet known to be able to support life, there's still lots to learn about our fascinating home planet

Like the TV show says, the Earth is indeed the third 'rock' from the Sun - it's also the largest of our Solar System's four terrestrial planets, the fifth-largest planet and the densest planet overall. It's called an oblate spheroid - it's flattened at the poles, but bulgy at the equator, thanks to forces from the Earth's rotation. The bulge means that the furthest point from the centre of the Earth to the surface is located in Ecuador. The Earth has a density of 5.52 grams per cubic centimetre, a mass of  $5.98 \times 10^{24}$  kilograms and a circumference of 40,075 kilometres (25,000 miles).

Earth rotates on its axis once approximately every 24 hours, although the length of a true solar day (measured from noon to noon) always varies slightly due to small changes and eccentricities in the planet's rotation and orbit. Speaking of orbit, Earth has an eccentric, elliptical one. It completes an orbit around the Sun once every 365.26 days, at a mean distance of 150 million kilometres (93 million miles). The axial tilt of 23.4 degrees means that the northern and southern hemispheres are exposed to

the Sun at different times, resulting in our four seasons.

The Earth is not the only planet to have a moon, but the relationship that we have with ours has had a measurable effect on everything from our climate to the length of our year. The Moon is tidally locked to the Earth - it has a rotational period that's the same length as it takes to orbit our planet. This means that the same side is always facing us. Tidal interaction means that the Moon is moving away from us at a rate of about 38 millimetres (1.5 inches) per year. The tides aren't just caused by the gravitational pull of the Moon, though; it's a complex relationship between the Moon, the Sun's gravity, and Earth's rotation. Not only do the tides cause sea levels to rise and fall, but they may also be what's keeping the Earth's tilt stable. Without it, some scientists believe, the tilt may be unstable and result in chaotic changes over millions of years.

Just as the Sun and Moon affect the Earth, our planet also has a noticeable effect on objects around it. Since the Moon's formation, the Earth has acted

like a bit of a cosmic bully, pushing and pulling it until it fell into line. There are other objects that Earth has an effect on as well. Asteroids, comets and spacecraft have all been hindered or helped by the Earth's gravity in their motion, unable to avoid the inevitable influence when they come into its vicinity.

An object falling freely near Earth's surface will experience an acceleration of about 9.81 metres (32.2 feet) per second every second, regardless of its size. Owing to the bulge mentioned earlier, this gravitational force is slightly different across the Earth. At the equator a falling object accelerates at about 9.78 metres (32.09 feet) per second every second, while at the poles it is closer to 9.83 metres (32.35 feet).

As you move away from Earth's surface the gravitational force decreases but at a barely noticeable rate. If you stood atop Mount Everest, at 8,848 metres (29,029 feet) tall, you'd weigh about 0.28 per cent less. Even at an altitude of 400 kilometres (250 miles), the gravitational force you'd feel is still 90 per cent as strong as it is on Earth's surface; the feeling of weightlessness in orbit is instead due to your horizontal velocity, which is so fast that you continually fall towards Earth.

Beyond Earth, our planet's gravitational pull continues to decrease, but in smaller increments. Even at a height of 2,000 kilometres (1,240 miles) you'd still experience a pull of just under six metres (20 feet) per second every second.

**"Tidal interaction means that the Moon is moving away from us at a rate of about 38 millimetres per year"**

## Orbits and seasons

### Northern summer

The northern hemisphere receives the most direct sunlight during the summer months, resulting in the hottest temperatures on the planet

### Northern spring

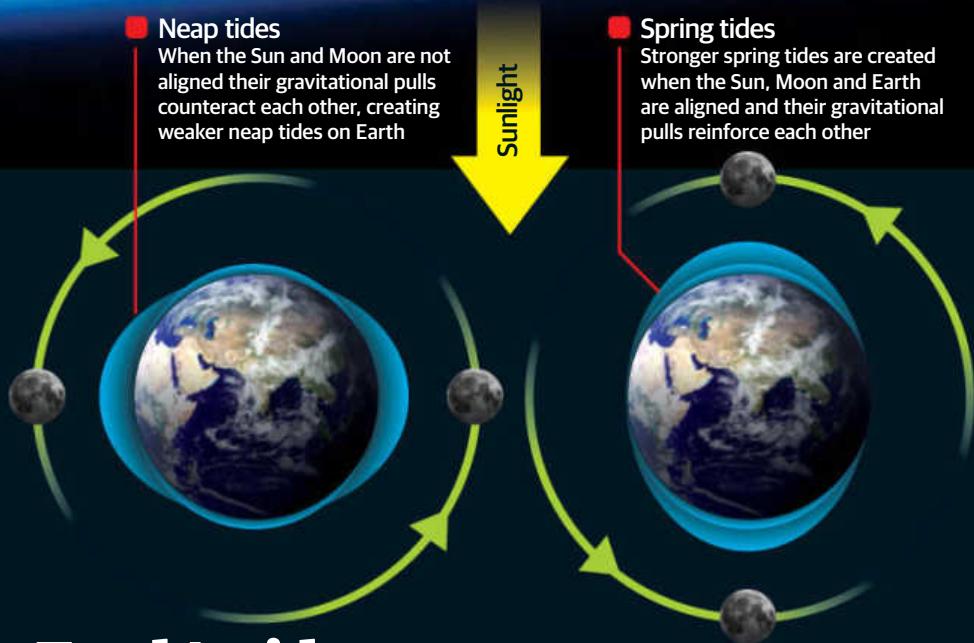
The Earth's degree tilt and elliptical orbit means that when the Earth is tilted towards the Sun, temperatures are warmer

### Northern winter

During the coldest months, the Sun's rays have further to go to reach the Earth. The seasons are reversed for the southern hemisphere

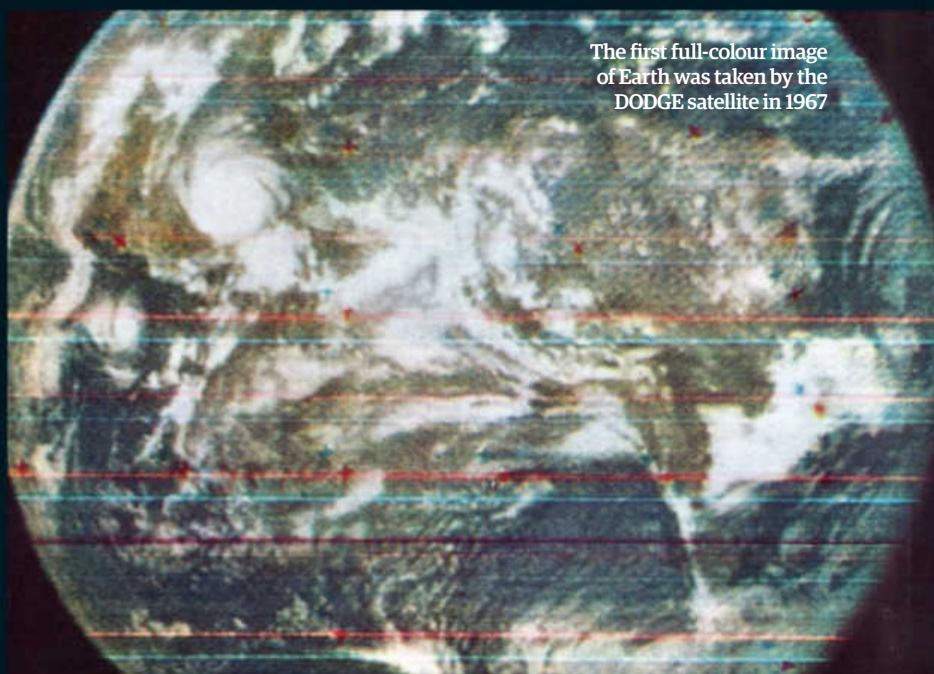
### Northern autumn

As the northern hemisphere begins to tilt away from the Sun and move away in its orbit, temperatures get colder



## Earth's tides

The alignments of the Sun and Moon affect the tides. The Sun's large mass means that the tidal forces it exerts on the Earth are half those of the Moon despite its distance from the Earth. At the first and third quarter Moons (above left), the Sun and Moon are in opposition and produce neap tides, which are lower amplitude. Higher-amplitude spring tides are produced during times of new Moon and full Moon.



## The planets in relation to the Sun

Earth lies 150 million km (93 million mi) from the Sun on average, known as 1 astronomical unit



# The Earth in numbers

Fantastic figures and surprising statistics about Earth

# 3,000

*There are around 3,000 operational satellites and 8,000 man-made objects (including decommissioned satellites) in Earth orbit*

# 17 days

*It would take about 17 days at 100km/h (62mph) to drive around the Earth*

# 360°

*It looks like a perfect sphere, but the Earth bulges at the equator and is flattened at the poles*

# 10cm

*The islands of Hawaii move about 10cm towards Japan each year*

# 5 billion

*The Sun will expand and become a red giant in about five billion years - likely engulfing all of the inner planets, including Earth*



# Earth inside and out

How Earth formed into the habitable world we know today

You may think you know all there is to know about Earth, but we take the wonders of our home planet for granted sometimes. It's unique because it's the only planet that has all of the elements needed to support life. It's also incredibly diverse, from the vast array of geographic features to the millions of plant and animal species. If you want to explore the unknown, there's no need to look to the stars; we're always discovering something new about our own planet.

But let's start with the basics. Along with the other planets, the Earth formed from the solar nebula - a cloud of dust and gas left over from the Sun's formation - about 4.54 billion years ago. It may have taken between 10 and 20 million years for the Earth to fully form. It started out as a molten planet, but a buildup of water in the

atmosphere cooled the outer layers, forming a solid crust.

The minerals found in the Earth are too numerous to mention, but just eight of them make up about 99 per cent of the entire Earth: iron, oxygen, silicon, magnesium, sulphur, nickel, calcium and aluminium.

From the inside out, the Earth comprises a core, mantle, crust and atmosphere. While the other terrestrial planets are also mostly divided this way, Earth is different because it has both an inner and outer core. The inner core is solid, while the outer core is liquid, and both contain mostly iron and nickel. The Earth's core is 6,700 degrees Celsius (12,100 degrees Fahrenheit) at the centre. This heat has two sources. The major source is radioactive decay, while about 20 per cent comes from energy generated by

the gravitational binding of the planet. At formation, the Earth's core was even hotter - it has cooled as some of the radioactive isotopes have depleted.

Enclosing the core is the mantle, which is divided into two layers - a highly viscous liquid, topped by a rigid rocky layer. Finally, there's the crust - a thin rocky layer separate from the mantle because the mineral make-up is different.

Of course, these are the layers of the Earth as we know them today - numerous processes over our planet's life span have influenced and changed its make-up. The Moon is one example. It formed not long after the Earth. There have been several theories as to how this happened, but the prevailing belief is that a large object about the size of Mars collided with the Earth. Some of the object's mass merged with the Earth, some shot out into space and some formed into the Moon.

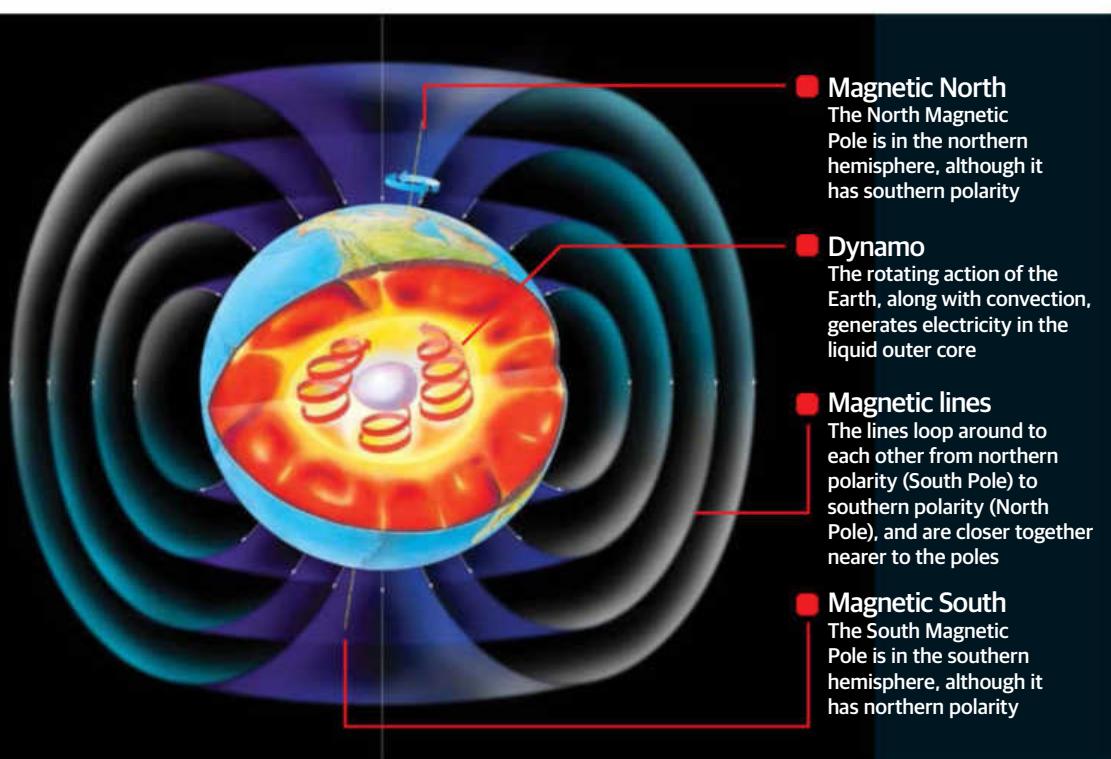
Asteroids, comets and other objects passing by deposited water and ice, ultimately leading to the formation of the oceans. The Sun was still forming at this time, too, and as its activity increased, so did the Earth's temperature. Volcanic activity and outgassing are responsible for the Earth's initial atmosphere. This multilayered atmosphere includes 78 per cent nitrogen, 21 per cent oxygen, and trace amounts of other elements. The layer of ozone blocks ultraviolet radiation from the Sun, protecting life below. Ozone is also part of the greenhouse effect, which helps sustain life on Earth. Gases trap heat rising from the surface, which keeps the average temperature at 15 degrees Celsius (59 degrees Fahrenheit).

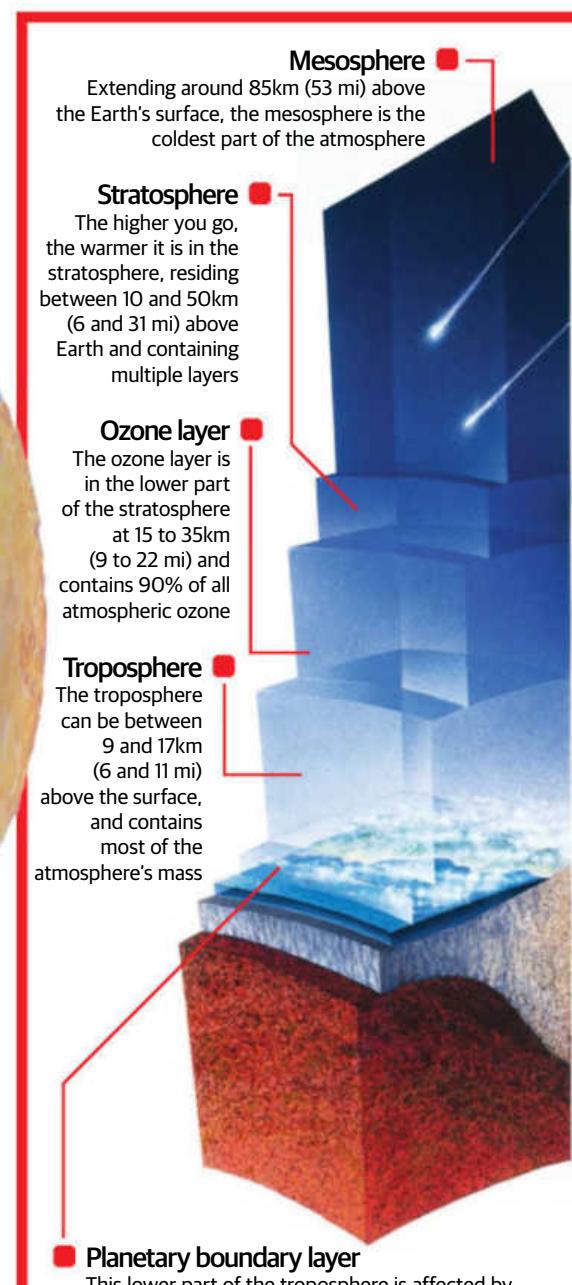
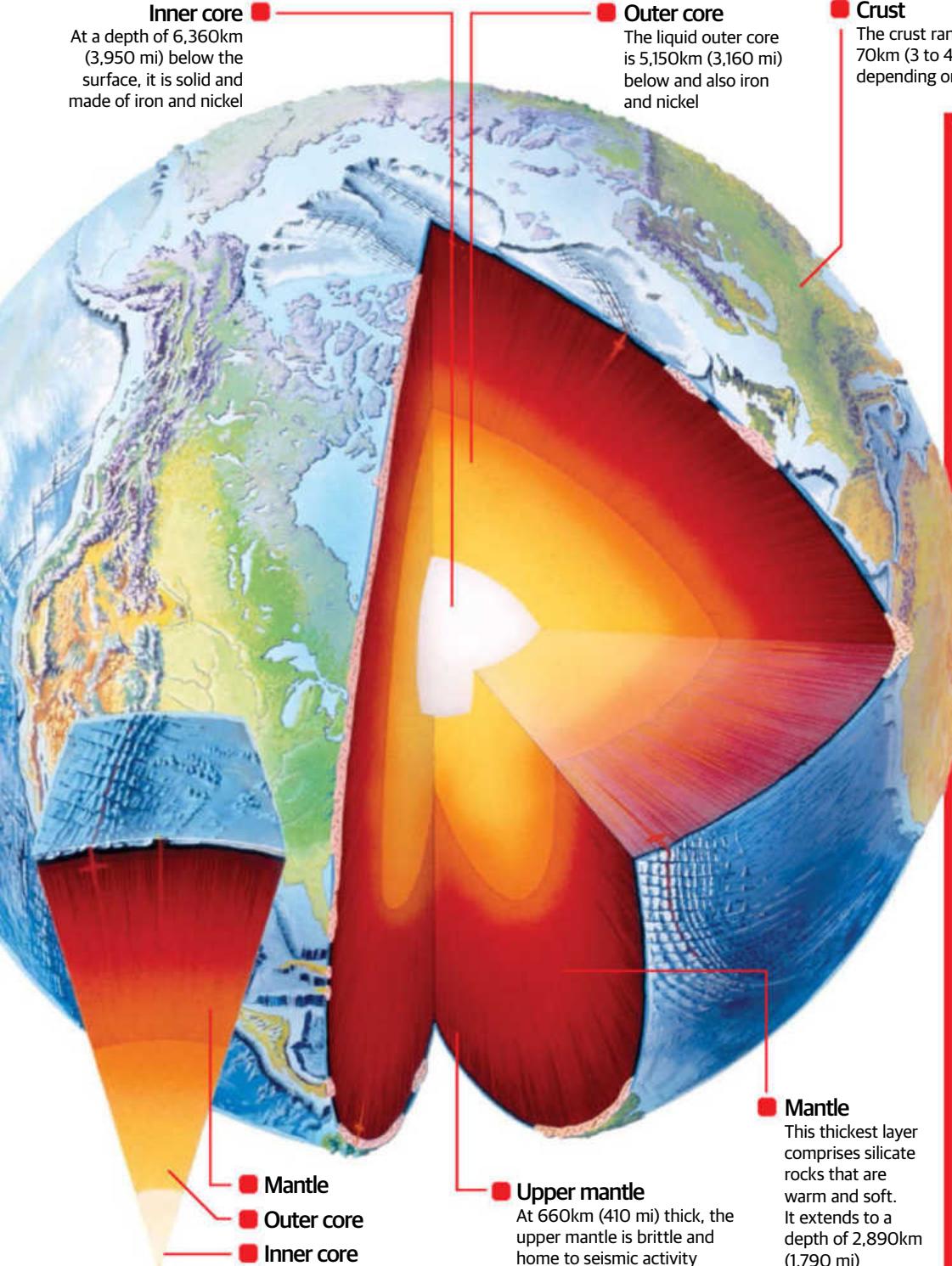
Beyond the thinnest, uppermost layer of the atmosphere, the troposphere, lies the magnetic field. It protected the gases in the atmosphere from being sheared away and carried off into space by the solar wind. The field surrounds the Earth and has poles that roughly correspond to the Earth's magnetic poles. ■

**"The Earth formed from the solar nebula - a cloud of dust and gas left over from the Sun's formation"**

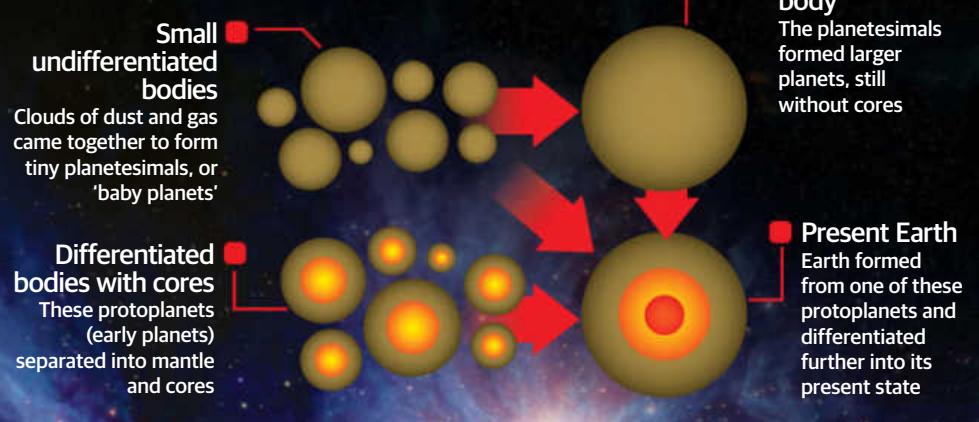
## Earth's magnetic field

The Earth's magnetic field is generated from its molten outer core, known as a dynamo. It's created when the liquid iron within rotates, convects and generates electricity. The field extends about 63,700km (39,500 miles) from the Earth on its Sun side and 384,000km (238,600 miles) on the Moon side. It's as if there's a bar magnet at the centre of the Earth, with northern polarity corresponding with the South Geographic Pole and vice versa, but in the Earth's case, the 'magnet' is tilted at about 11 degrees. Every several hundred thousand years, the magnetic poles swap with each other. Magnetic lines extend from each pole and loop around to each other, with the lines spreading further apart as they move out from the centre. The solar wind also distorts the lines, and the field moves over time with shifts in the dynamo.





## How the Earth formed



## Earth's atmosphere

Earth is the only planet in the Solar System with an atmosphere that supports life. It was oxygen-rich initially thanks to the prevalence of water in the form of gas, ice and liquid, which came from its formation and other astral bodies. Some of the gases were released by activity on Earth while it was forming, and others came from organisms living on our planet. Carbon dioxide, for example, is necessary for plant growth. The plants in turn release oxygen. Carbon dioxide also helps to keep the planet warm enough to sustain life. The ozone layer traps in heat, too. But without the pull of gravity and the magnetic field, Earth would've lost its atmosphere long ago.

# On the surface

Our planet is changing all the time, all the way down to its mantle

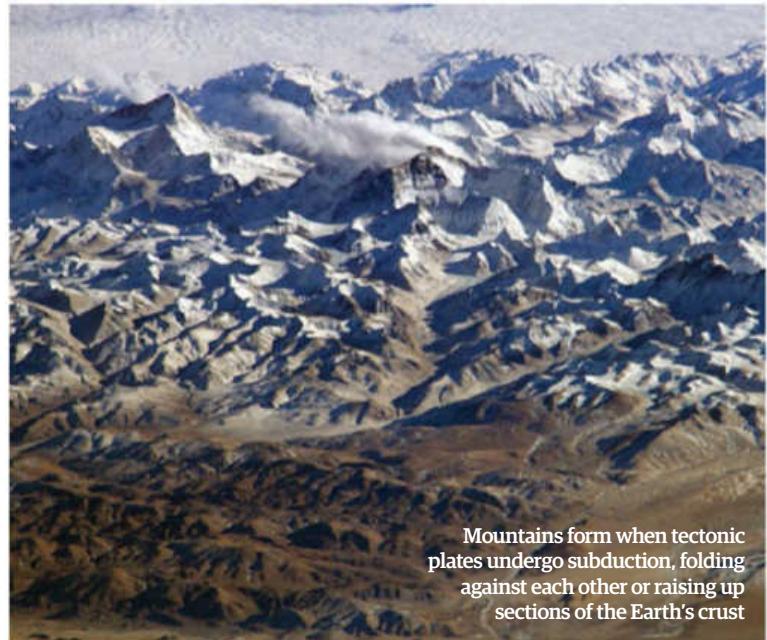
While we typically divide the Earth into crust, mantle and core, there are other ways of differentiating the outer layers. The lithosphere comprises both the crust and part of the upper mantle - specifically, the part that is rigid but has elasticity and becomes brittle over thousands of years.

Underneath is the asthenosphere, a deeper part of the mantle that behaves like a viscous fluid. The lithosphere is divided into tectonic plates, pieces that are about 100 kilometres (62 miles) thick and move on top of the flowing asthenosphere. There are seven major plates: African, Antarctic, Eurasian, Indo-Australian, North American, Pacific and South American. These include the continents and the Pacific Ocean, while smaller plates make up the rest of the Earth. They can comprise continental crust (which is mostly granitic rock), oceanic crust (mostly mafic rock), or some of both. Continental crust is thicker but not as dense as oceanic crust.

Plate movements occur at the boundaries between them. At convergent boundaries, plates can move under each other (or subduct) or collide in the case of continental

crust. At divergent boundaries, the plates slide away from each other. Plates grind along each other at transform boundaries. Volcanoes and earthquakes often occur along boundaries between plates. Plate boundary movement is also responsible for creating oceanic trenches and mountains. Some plates have hot spots - areas of volcanic activity under the mantle within the plate, where volcanoes often form. While material can be lost through subduction, more is formed along divergent boundaries in a process known as sea floor spreading. That's why some scientists call it a sort of conveyor belt - there's constant motion and change, but the total surface area of the Earth remains the same.

There are a few theories about what makes the plates move. The lithosphere is much denser than the asthenosphere, so we understand why it can slide, but where does the energy come from? One view is that it's from dissipating heat in the mantle, but the plates may move due to gravitational pull, forces coming from the Earth's rotation and the gravitational pull from the Moon or the Sun. ■



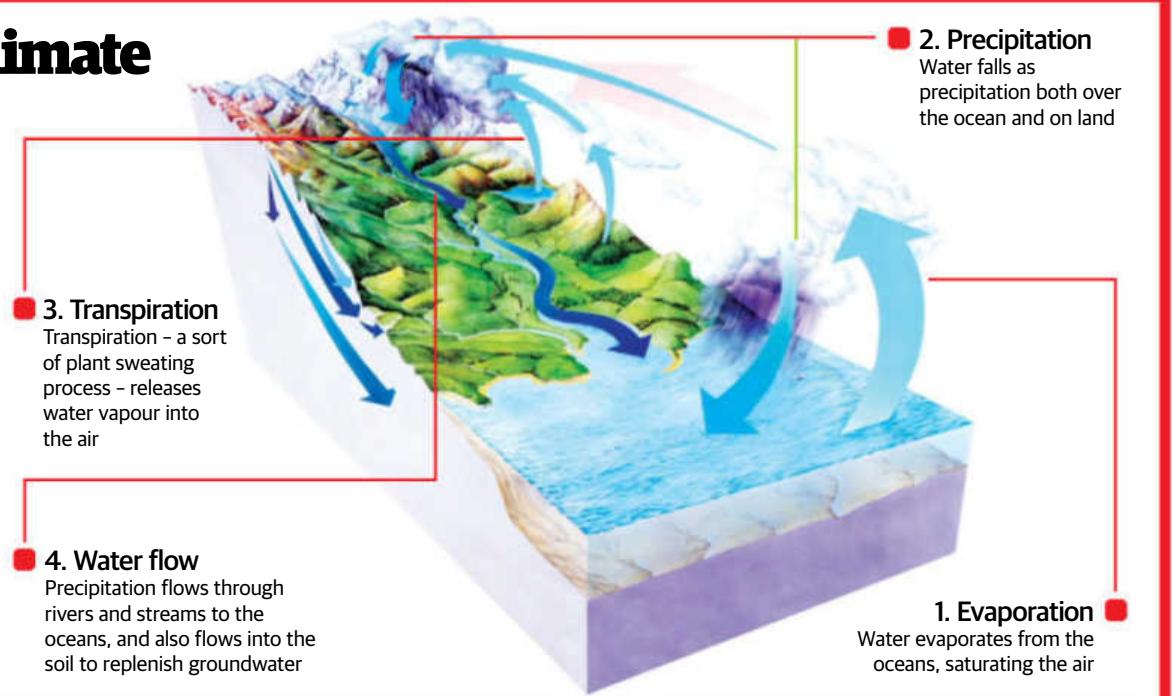
Mountains form when tectonic plates undergo subduction, folding against each other or raising up sections of the Earth's crust

**"Some plates have hot spots - areas of volcanic activity under the mantle within the plate, where volcanoes form"**

## Weather and climate

Energy from the Sun heats the air in the lowest level of our atmosphere, the troposphere, causing it to expand. Warm, lower-density air rises, while cooler, high-density air sinks. This is called atmospheric circulation. Along with the ocean currents, it's responsible for the movement of heat in the air and powers our weather and climate.

The same atmospheric circulation that distributes thermal energy also transports water vapour, present in the atmosphere from evaporation and transpiration. Warm air rises, falling as precipitation. The amount and kind of precipitation depends on temperature and other features. Once it falls, it replenishes oceans, lakes and groundwater, some of which rises again through evaporation. This is known as the water cycle.



# Earth's fault lines

## Pacific Plate

This plate lies beneath the Pacific Ocean and is the Earth's largest plate

## North American Plate

This plate extends from the Mid-Atlantic Ridge along the floor of the Atlantic Ocean to the Chersky Range in Siberia. It has divergent, convergent and complex boundaries

## Eurasian Plate

This plate includes all of Europe and much of Asia as well as oceanic crust from the Mid-Atlantic Ridge to the Gakkel Ridge

# All About Earth

## Surface features



### Desert

Deserts get so little precipitation that they can't support much life, but there are desert-dwelling plants and animals. A true desert gets less than 400mm (16in) of rainfall per year. They make up about one-third of the Earth's land surface.



### Rainforest

Rainforests have very high levels of rainfall, usually a minimum of 1,750mm (68in) each year. They cover 5% of the Earth and are the source of about 25% of our natural medicines, and home to millions of species of plants and animals.



### Oceans

Saline or saltwater makes up about 71% of the Earth's surface. No other observable planet has as much water on its surface. The total volume of saltwater on Earth is approximately 1.3 billion cubic kilometres (31 million cubic miles).



### Ice caps

Ice caps and glaciers cover about 10% of the Earth's surface, and hold about 70% of our freshwater. Glacier movement helped shape the topography of the land in many areas. If they all melted, our ocean levels would rise by 70m (230ft).

## South

## American Plate

Including South America and much of the Atlantic Ocean, this plate has complex, convergent and divergent boundaries. It is moving away from the Mid-Atlantic Ridge

## Plate tectonics

### Sea floor spreading

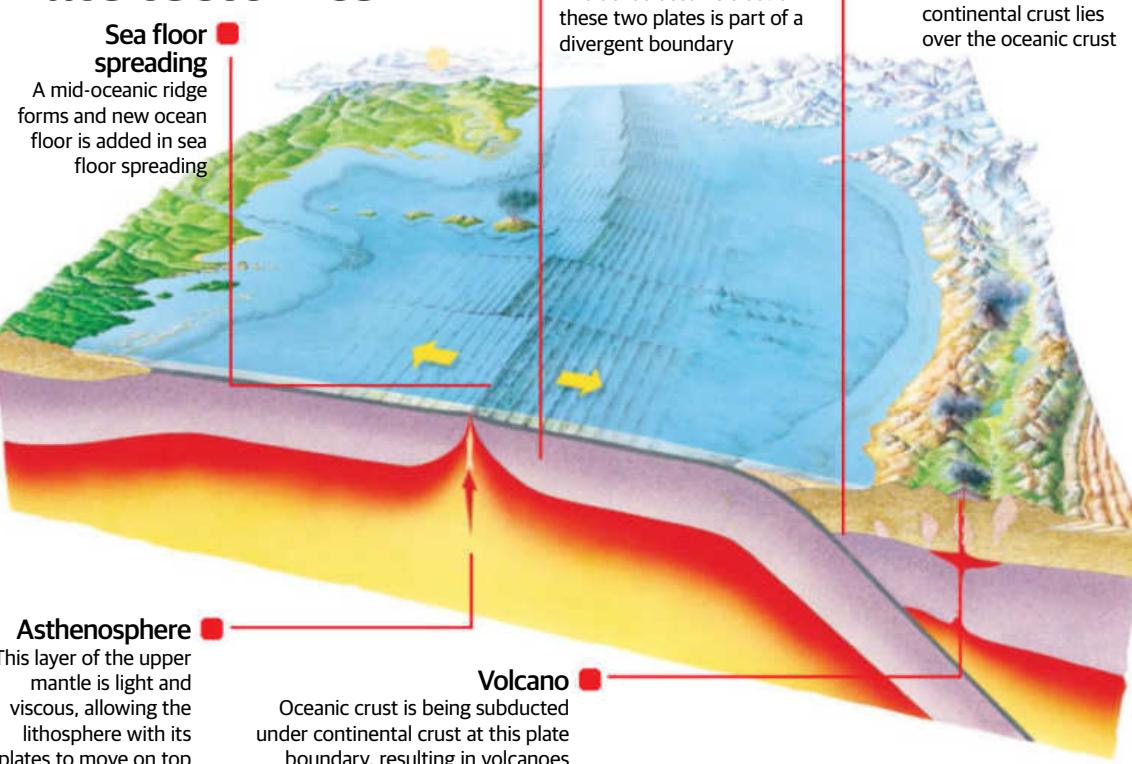
A mid-oceanic ridge forms and new ocean floor is added in sea floor spreading

### Oceanic crust

The dense oceanic crust of these two plates is part of a divergent boundary

### Continental crust

The lighter, thicker continental crust lies over the oceanic crust



### Asthenosphere

This layer of the upper mantle is light and viscous, allowing the lithosphere with its plates to move on top

### Volcano

Oceanic crust is being subducted under continental crust at this plate boundary, resulting in volcanoes



# Why is there life on Earth?

The Earth has the perfect recipe to support life. But why?

Astronomers have coined the term 'Goldilocks Zone' to describe star systems that theoretically have planets with atmospheres capable of retaining water. All known forms of life require liquid water, so this has become the gold standard for finding life on other planets. They may also be called circumstellar habitable zones (CHZ). But a planet needs more than just water – other bodies within our Solar System are believed to have it but we still haven't found life there. Earth is 'just right' for a number of reasons.

The atmosphere is one. All known forms of life require oxygen-rich air, and our atmosphere is full of it. It's being continually replenished by plant respiration and by the water cycle. Thanks to the Earth's gravity and its

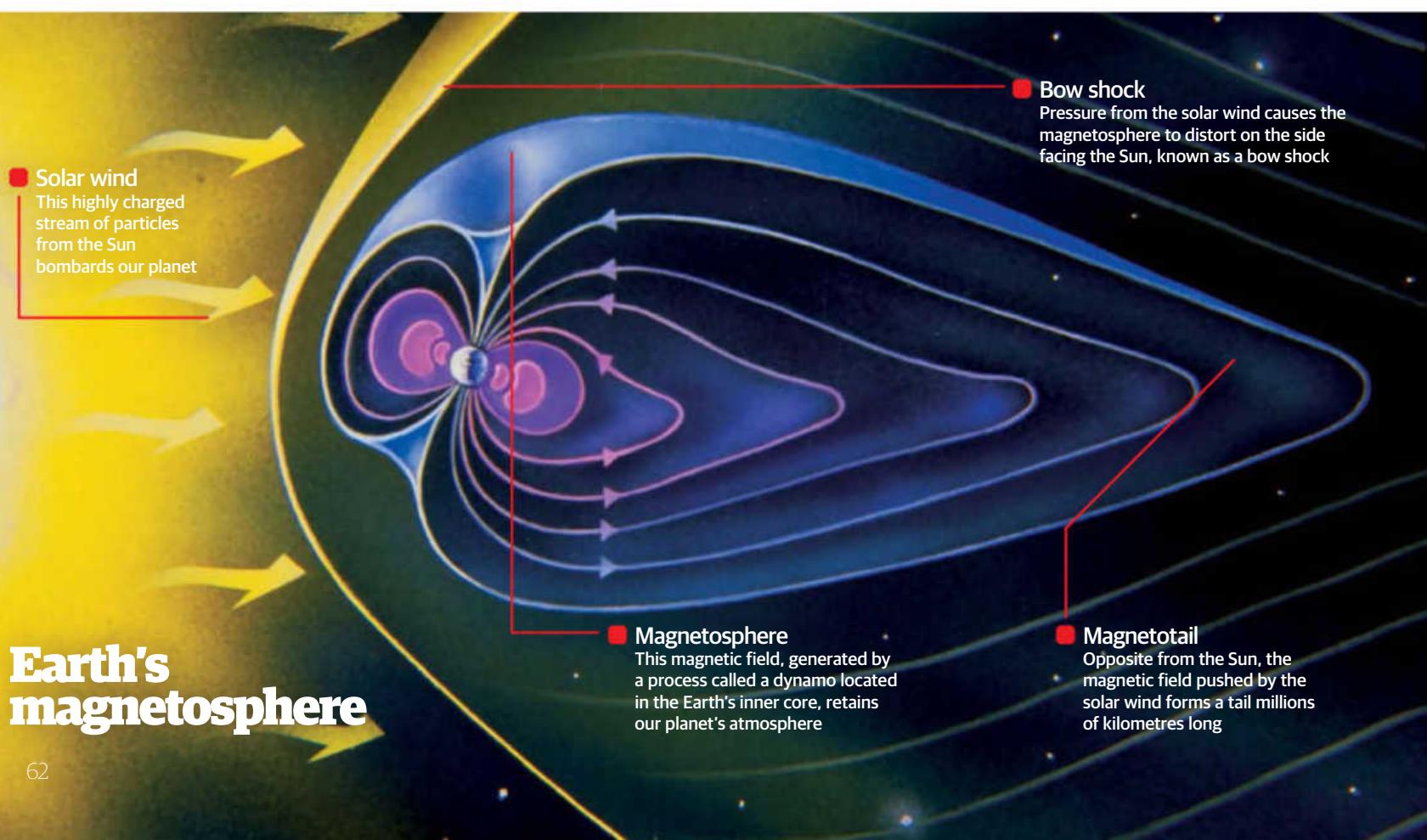
magnetic field, the atmosphere stays put and hasn't been swept out to space. Our Sun is also an important factor, because the Earth is the perfect distance from it, with temperatures and heat levels that, while varied, allow life to grow and thrive. Sunlight is also necessary, because without enough sunlight, plants on the Earth would not be able to photosynthesise.

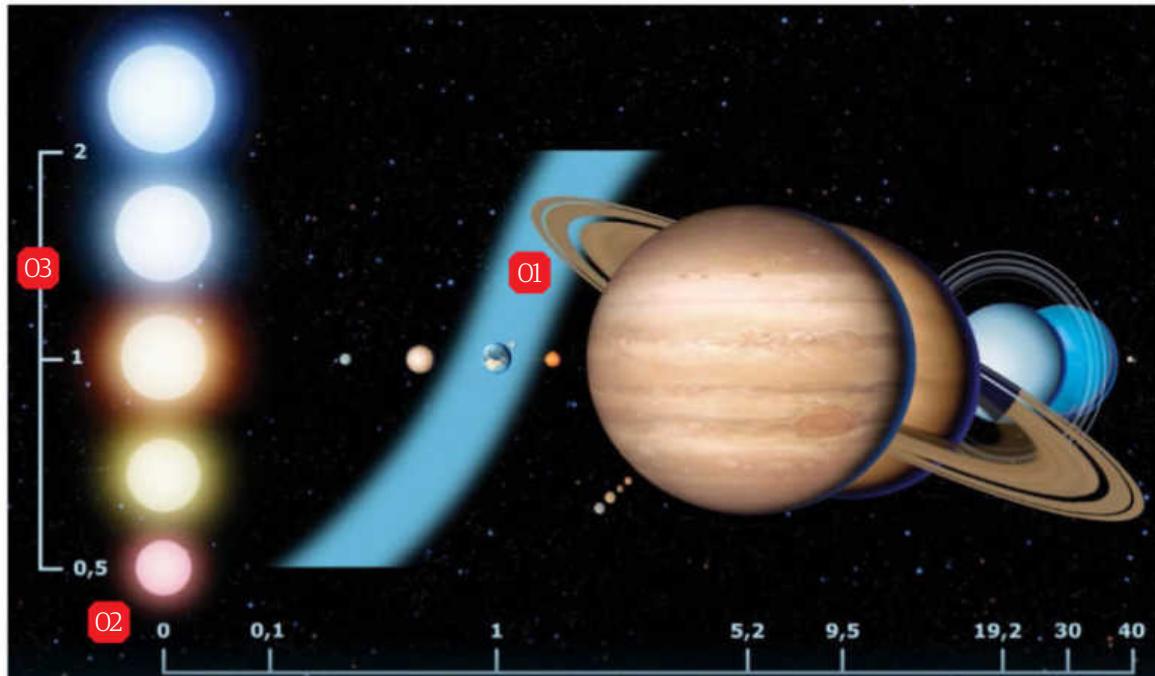
The water cycle, proximity to the Sun, sunlight and atmosphere all contribute to a suitable climate for life. While temperatures vary across the globe, Earth doesn't experience the extreme swings of other planets. On Mars, it can be as warm as 25 degrees Celsius (77 degrees Fahrenheit) but as cold as minus 140 degrees Celsius (minus 220 degrees Fahrenheit). ●



## Water

Although other planets have been found to have water, none have as much as Earth. Sometimes our water mass, including the oceans and freshwater sources, is known as the hydrosphere. Without such plentiful sources, the water cycle could not function and there wouldn't be enough oxygen to support life. Human bodies comprise about 70 per cent water, and life on Earth needs it to survive.





## The Goldilocks Zone

### 1. Habitable Zone

This narrow band shows that Earth is the only planet in our Solar System known to be capable of sustaining life.

### 2. Radius of planet's orbit relative to Earth

Earth is at '1'. The other planets are too big or too small to support life.

### 3. Stellar mass relative to the Sun

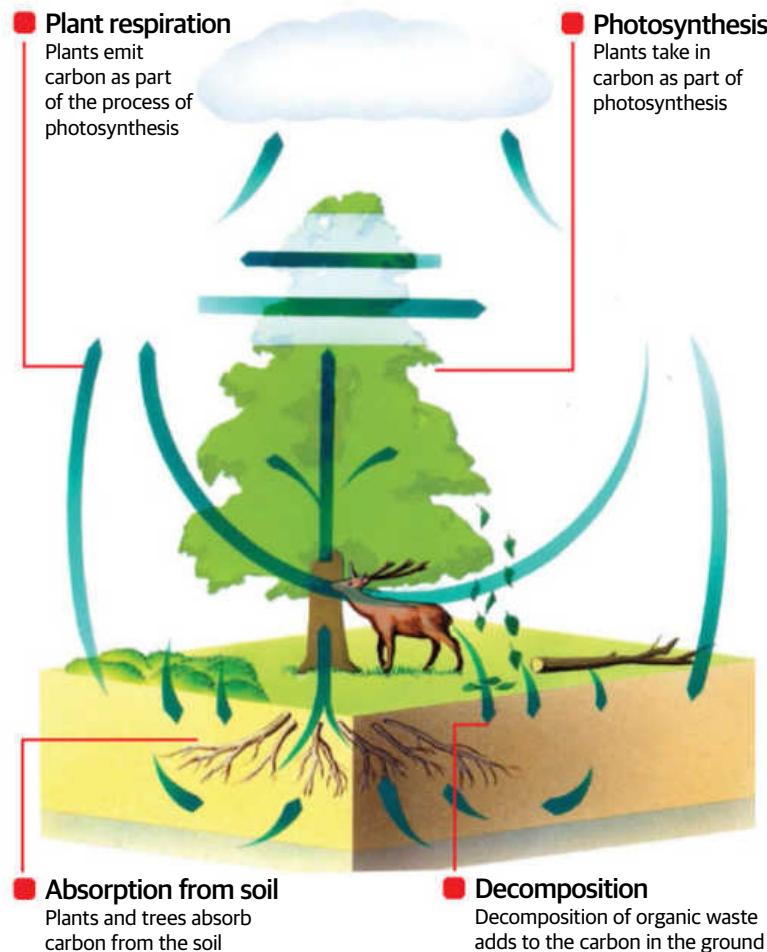
The Sun also has the perfect mass of any known star to provide the right amount of light and energy to the Earth.

## Carbon

The carbon cycle is just as important to our climate and survival on this planet as the water cycle.

Carbon dioxide is an element of the greenhouse effect, which traps heat in and keeps our planet at a regular temperature, maintaining our regular climate. Most of the life on our planet is carbon-based, with this abundant element bonded to other elements to create the building blocks of life. It is replenished in the atmosphere by plant and microbial respiration, as well as decomposition of organic materials.

**"The atmosphere is being continually replenished by plant respiration and by the water cycle"**



## 5 kingdoms of life



### Animalia

The animal, or Animalia, kingdom (also called Metazoa), includes about 1,000,000 multicellular, heterotrophic species.



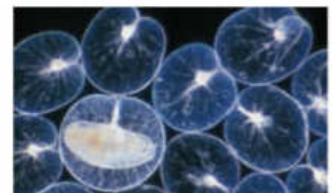
### Plantae

Kingdom plant, or Plantae, includes everything from multicellular flowers to mosses. There are about 250,000 plant species.



### Fungi

Fungi include around 100,000 identified species. The Fungi kingdom includes mushrooms, yeasts and moulds.



### Protista

The Protista kingdom has 250,000 species which don't have much in common with each other, apart from not belonging elsewhere.



### Monera

The Monera kingdom is made up of species such as algae and bacteria. There are approximately 10,000 species in this kingdom.

# Observing Earth

Checking out our home planet has become easier over time

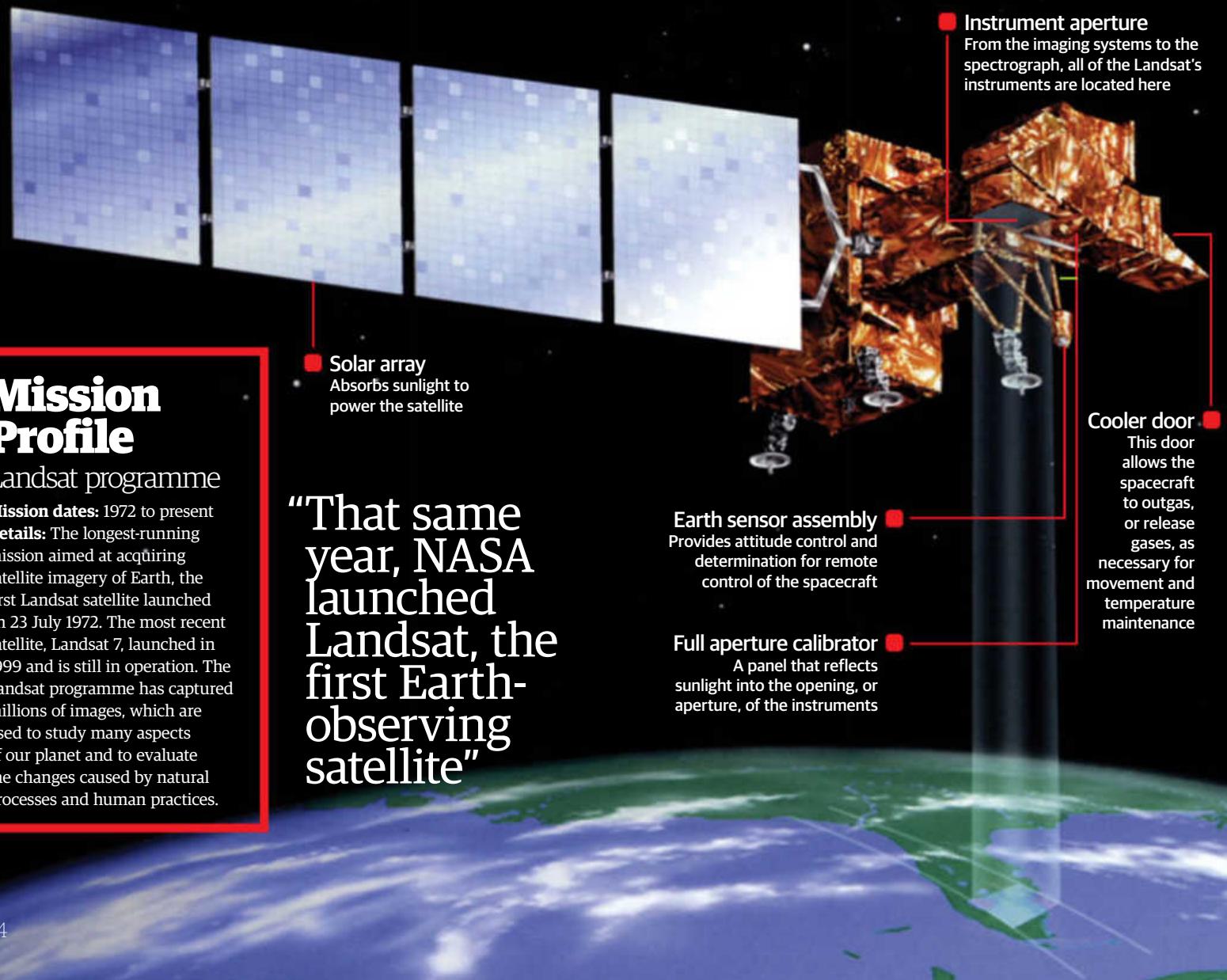
Until we were able to get far enough away from our planet to view it, the only way we could infer things about it was by exploring its relationship to other heavenly bodies. And for a long time, what we believed was wrong. Many ancient cultures, for example, believed that the Earth was the centre of the universe. This was based on two observations: the stars and other planets appeared to revolve around the Earth, and to a person on Earth, the planet seemed to be perfectly at rest. Once we were able to better observe other bodies,

we began to learn the truth about our home planet. Then we developed the technology to take pictures of the Earth from space. The first such image was taken by a rocket, shot 56 kilometres (35 miles) into the air over New Mexico, USA in 1946.

We've come a long way since then. The Freedom 7 spacecraft, carrying the first American into space, went up in 1961 and returned some amazing images of the Earth's surface. But the first fully illuminated photo of Earth was taken by astronauts aboard the Apollo 17 spacecraft in

1972. Known as 'The Blue Marble', it became one of the first photos to be widely distributed. That same year, NASA launched Landsat, the first Earth-observing satellite. It continues to operate today, sending back images that have been used in everything from agricultural planning to national security. Today there are dozens of Earth-observing satellites - some commercial, some sent up by NASA, the ESA or other space agencies around the world. These satellites don't just take pictures; they monitor the weather, climate

and environment. Geostationary Operational Environmental Satellites (GOES), for example, are a system of satellites that have been used in meteorology and weather forecasting since 1975. The latest Earth-observing satellite, Suomi NPP (Suomi National Polar-orbiting Partnership), is a joint project between NASA, the NOAA (National Oceanic and Atmospheric Administration) and the Department of Defense. Launched in 2011, it is part of a new generation of satellites and is used to track weather, climate and other environmental changes. ■





Highest mountain



Largest rainforest



Biggest active volcano



Largest glacier



Biggest ice sheet

## 8 stunning Earth landmarks

### Largest rainforest

One in ten of the world's known species live in the Amazon rainforest.

### Biggest active volcano

Mauna Loa in Hawaii is the largest active volcano on Earth in terms of volume and area.

### Tallest waterfall

Situated in Venezuela, Angel Falls stands at 979m and is the world's highest uninterrupted waterfall.

### Biggest crater

With a 300km diameter, the Vredefort crater in South Africa near Johannesburg is Earth's largest known impact crater.

### Deepest canyon

The Tsangpo Canyon in Tibet can reach depths of over 6,000m.

### Biggest ice sheet

The East Antarctic Ice Sheet is the largest ice sheet on the planet and is home to the South Pole.

### Largest glacier

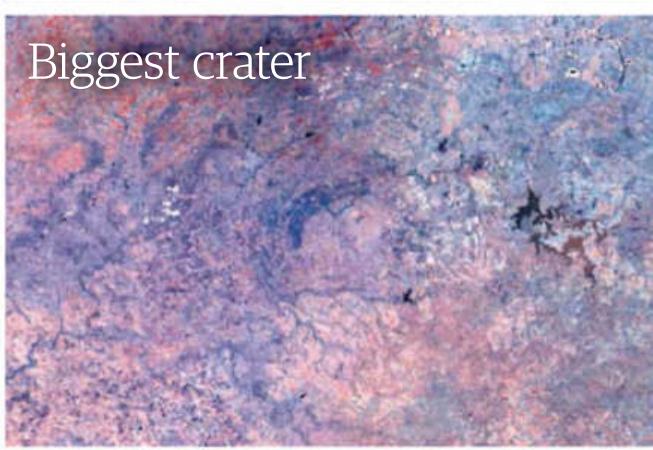
Antarctica's Lambert Glacier is about 100km wide, over 400km long and about 2,500m deep.

### Highest mountain

At 8,848m tall, Mount Everest is the highest mountain on Earth.

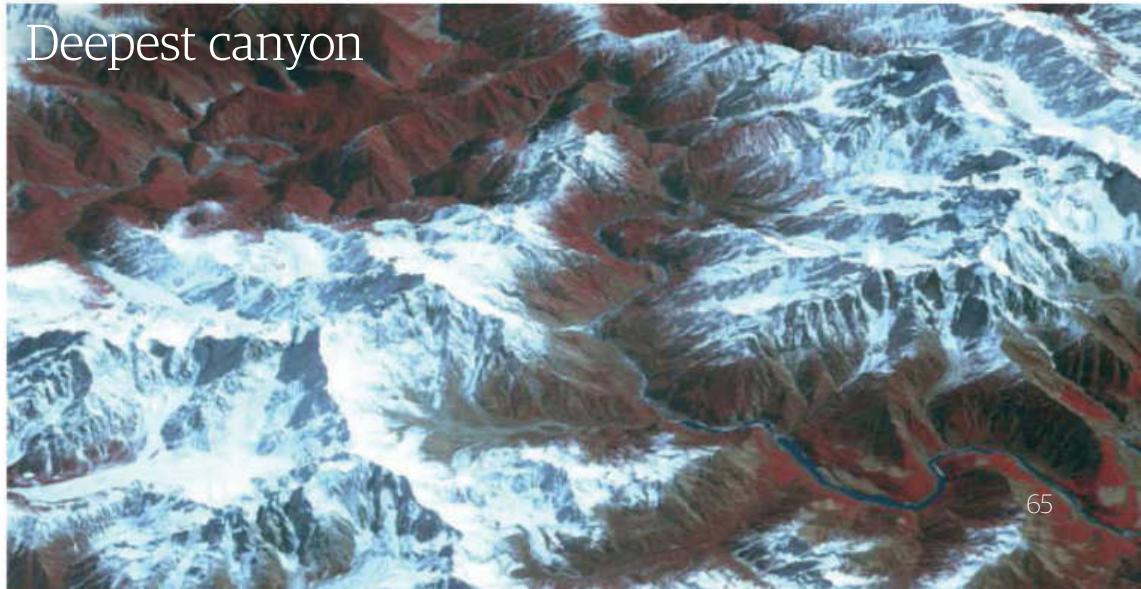


Tallest waterfall



Biggest crater

### Deepest canyon





Earth & Moon





# OUTPOST EARTH

From spacewalking in water to living in the desert, we look at how astronauts train for the challenges of exploring moons, asteroids and planets on Earth

On 4 November 2011, six triumphant men from across the world returned to Earth and emerged from a windowless isolation chamber to elated cheers. They had - in theory at least - been to Mars and back on a journey that had taken them away from their friends and families for 520 days. During that time, three crew members had spent 30 days on the Red Planet, having detached from their mother ship to explore the Martian surface, removed soil and rock samples and planted three flags; one each for the Chinese, Russian and European space agencies.

Their time away proved tough. The mission affected their sleep patterns, with one crew member's body falling into a 25-hour day cycle. And although

they had books, DVDs and the videogame *Guitar Hero* to occupy them, they had become bored and demotivated by the monotonous journey. Their activity levels lowered, their body temperature dropped by an average of 0.4 degrees Celsius (32.7 degrees Fahrenheit) and they were at risk of bone and muscle wastage. They may have lived in harmony but the three Russians, two Europeans and one Chinese were, it could be surmised, spaced out at least some of the time.

And yet the six hadn't actually ventured away from Earth at all. Their spacecraft was nothing more than a series of steel tubes at the Russian Institute for Biomedical Problems in Moscow. The landing module

was also a cylinder that had been made to feel like a Mars landing ship. The planet surface was simply a large room with a high, domed ceiling and a floor covered by red sand and rocks over which the crew had walked dressed in Orlan spacesuits. Everything had been a test, albeit one carefully constructed to be analogous to the expected isolation and challenge of a round trip to Mars.

Called Mars 500, the analog mission was of great use to scientists, engineers and astronauts preparing for a real-life future mission to Mars. By observing the experience of the crew, examining their physical and mental health and testing new technologies, experts were able to learn many lessons vital for



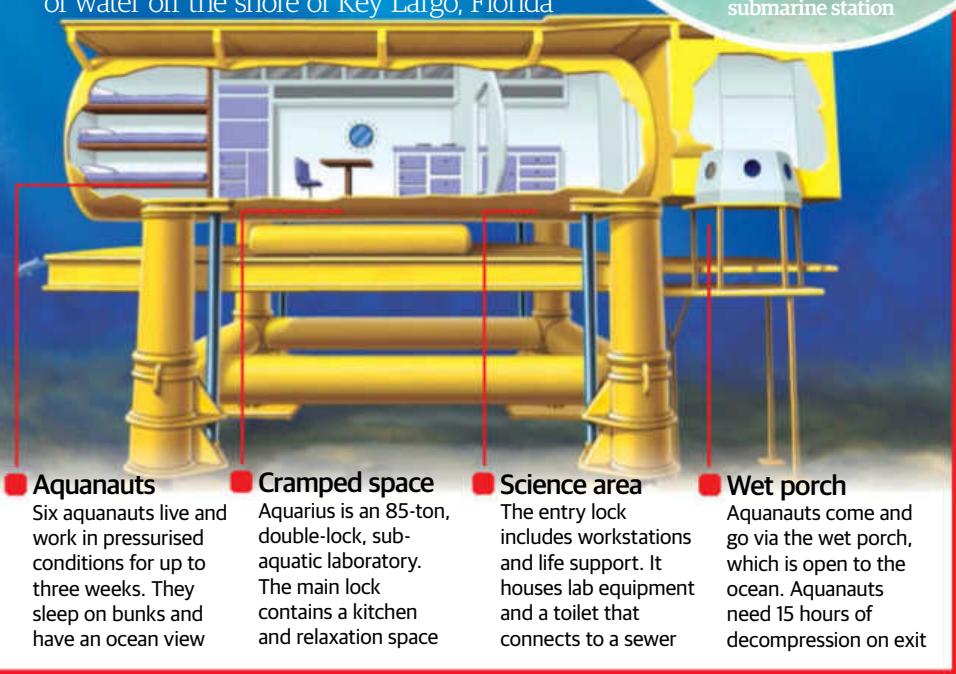
round trips to the Red Planet. "We were able to simulate the isolation astronauts would feel," explains Jennifer Ngo-Anh, ESA's Mars 500 programme manager. "The main purpose was to study whether, from a survival and interpersonal point of view, we could put a crew of six in a spacecraft for such a long time. We were looking at the psychology of the crew, their social interaction and cultural differences. We wanted to know how they would cope with the life support system we had in place and a limited water supply. The only things that were missing were simulations for microgravity and radiation."

Mars 500 is one of many analog missions - some of which also create artificial, simulated conditions. But analog missions also make use of the extreme environments found on Earth. One such mission is NEEMO, or NASA Extreme Environment Mission Operations. It involves sending six aquanauts to live underwater in a laboratory called Aquarius, some 5.6 kilometres (3.5 miles) from the shore of Key Largo in Florida. There they are isolated but they also get to experience reduced gravity in what is the world's only operating undersea lab.

Aquanauts can spend as long as three weeks on a NEEMO mission, living and working underwater. For missions on the bed of the ocean, they wear diving suits and oxygen tanks in place of spacesuits. They embark on sewalks that, just like a spacewalk, are carefully planned and restricted in time. Their mobility is slowed and their movement is difficult, mimicking the effort they would need to make when exploring a planet like Mars. In doing this, NEEMO is able to simulate Moon and asteroid missions, testing equipment and operational concepts.

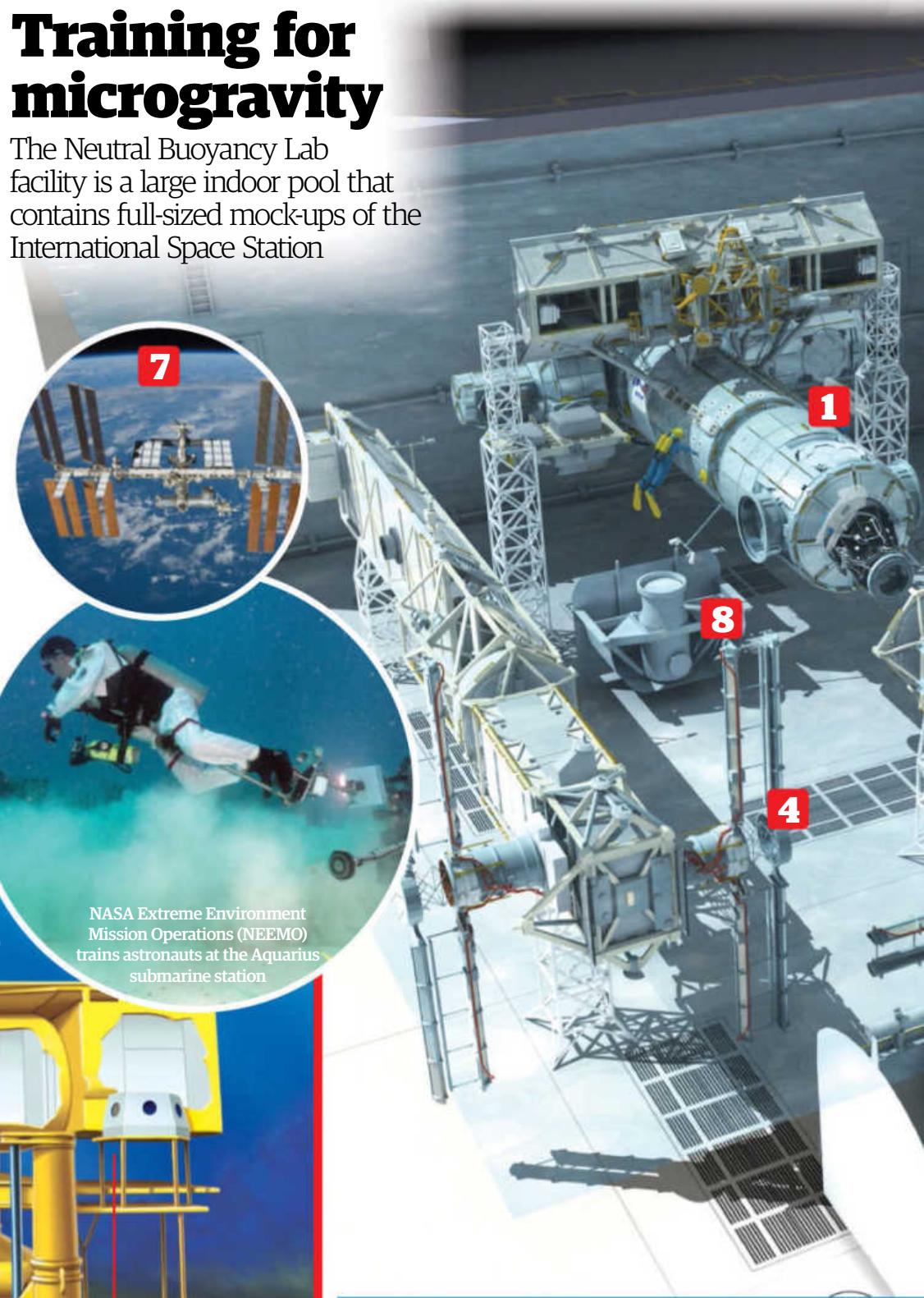
## Asteroid mission preparation

Aquarius is the world's only submarine research station, found in 19 metres (62 feet) of water off the shore of Key Largo, Florida



## Training for microgravity

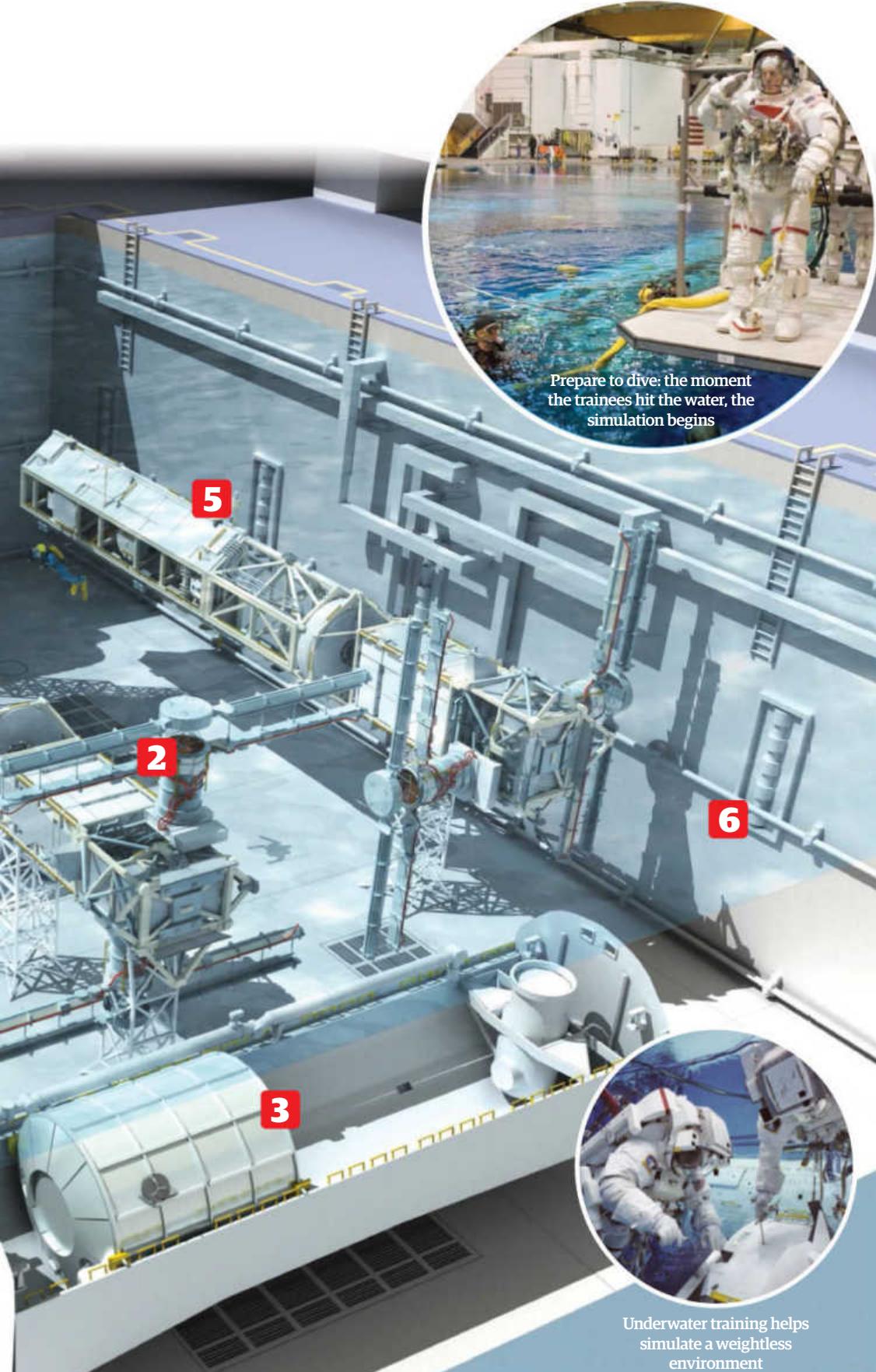
The Neutral Buoyancy Lab facility is a large indoor pool that contains full-sized mock-ups of the International Space Station



**1. The US lab**  
A replica of the ISS still doesn't fit directly into the pool. It is bent into the so-called wishbone configuration we see here.

**2. P6 segment**  
By allowing astronauts to view the segments of the ISS's truss (backbone), they can familiarise themselves with its structure.

**3. Cargo bay**  
This part of the ISS mock-up shows the cargo bay of the Space Shuttle Orbiter, which is used to deploy to or retrieve payloads from Earth.



**Underwater training helps simulate a weightless environment**

**4. S4 segment**  
As astronauts approach these segments underwater, they will experience the weightless environment of space.

**5. P1 segment**  
Water is the best environment for spacewalk training on Earth. Being able to move in their suits, use handrails and pass objects is vital.

**6. NBL tank**  
The Neutral Buoyancy Laboratory tank is a huge 62 metres (202 feet) long, 31 metres (102 feet) wide and 12 metres (40 feet) deep.

**7. The ISS**  
The ISS is 110 by 73 metres (361 by 240 feet). In the NBL, astronauts can practise installing and maintaining components in space.

**8. Docking system**  
When a shuttle docks with the ISS, it is important that a secure connection is achieved. Astronauts can practise it here.



## What is microgravity?

In space, gravity exists but in a reduced form. On the International Space Station, for example, gravity is around 88 per cent of that found on the Earth. But, because astronauts are in free fall, they appear to float. That's because free falling means they are falling towards and yet around Earth. This is thanks to the pull of the Earth and the speed at which the ISS and spacecraft are moving to match the curvature of the Earth. Referred to as microgravity, it can happen inside a spacecraft or outside on a spacewalk. By simulating microgravity, even for a limited time, astronauts can be better equipped for real-life space missions.

## Hervé Stevenin

EVA and Zero-G instructor for ESA astronauts



Hervé Stevenin leads ESA's Neutral Buoyancy Facility Operations. With more than 20 years of training experience, he is a spacewalk instructor for European astronauts.

### Why is underwater training useful for astronauts?

Astronauts have to perform EVAs and so we need an environment of weightlessness. Although we can use reduced gravity aircraft, they only give astronauts 23 seconds of pure weightlessness or microgravity. This is not appropriate for EVAs because they are six hours long and astronauts have to work on modules and in a complex environment. So we use an underwater environment to simulate the weightlessness and the astronauts feel like they are in a controlled buoyancy environment.

### How closely can simulation match real life?

The astronauts can work in a big water tank, into which we submerge big modules of the station. The modules are full scale and they have all of the EVA-related equipment like handrails on them. The astronauts can use the same kind of tethers and tools for the work underwater that they would carry out in space outside a station so it's equally demanding psychologically and physically. We teach astronauts to be efficient in the way they work. They need to be aware of the environment and communicate well. Not all astronauts can do an EVA: NASA and the Russians put all astronauts through a basic EVA training programme and they then assess who are the best ones. Only the best will continue.



## Earth & Moon

As part of the analog mission, aquanauts will spend a lot of time in a purpose-built habitat. All six will live together in cramped conditions and their ability to work together and support each other is closely studied. Each crew member is trained to deal with fire in the module as well as potential toxicity in the atmosphere.

While two Aquarius technicians are responsible for maintaining the habitat and also live with the astronauts, and while there are safety divers accompanying the crew, part of the analog mission is to limit outside assistance, with communication channels delayed by five minutes. The sense of isolation is also very real: travelling back to the

## Loredana Bessone

CAVES course and mission director



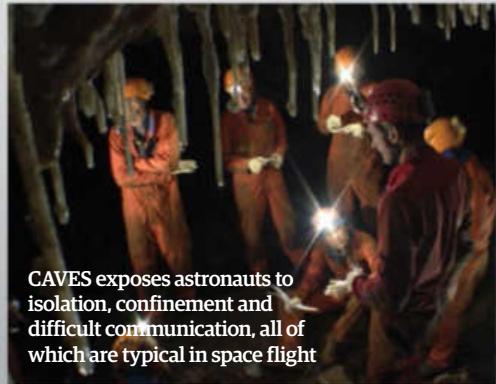
Loredana was hired by ESA for a student job in 1990 and within a few years had begun work on human space flight. She went on to develop astronaut operational skills training including ESA's CAVES.

### What were you looking for when you developed CAVES?

I was looking for an environment very similar to that which astronauts would encounter during human space flight so I wanted isolation, confinement, limited resources and difficult communication. There had to be real risk to create stressors that are typical on human space flight and a real mission that would allow astronauts to work together effectively and safely as an international team.

### How can you be sure simulations match real life experiences?

CAVES is a good analog. If anything, it can be even worse in a cave; more isolating than on a space station. Communication is achieved by a wire up to the base camp but if you just twist an ankle or a wrist you have to be carried out. You have to pay attention to everything you do because you only have the very limited visibility given by your headlamp. It's just like on an EVA where astronauts have limited visibility through their helmet. You can get disorientated so it is very important to have situational awareness at all times.



CAVES exposes astronauts to isolation, confinement and difficult communication, all of which are typical in space flight

sea surface is arduous and it requires aquanauts to undergo a 16-hour decompression sequence in order to protect the crew members from falling ill with decompression sickness.

"It takes even more time to come back to the surface than it takes to get back from the International Space Station to Earth, so this means the risks are real," says Hervé Stevenin, who was selected to be a crew member of the NEEMO 19 mission in September 2014.

By ensuring there is no quick 'get out', the mission is able to test the resolve of the aquanaut and his or her ability to be an astronaut. They are given a full flavour of the scientific tasks they are expected to carry out too, drilling down into the sea ground to collect samples. Sometimes the crew members are separated and sent to different landmarks, allowing them to recognise geological features of interest to the exploration. They are asked to take distance measurements and the dimensions of items they are studying. They have to send images and video from their helmet cameras to mission control. "It really gives you a feel for what it is like to be a space crew member," says Stevenin, who also leads ESA's Neutral Buoyancy Facility Operations. But it also lets the mission leaders figure what works effectively and what needs to be re-examined.

There are also secondary objectives. Scientists can conduct human physiology experiments during a NEEMO mission, which helps when optimising the planning, technology and expectations of science research during space explorations. With planned human crewed missions to Mars, such analog missions will certainly prove useful when training the next generations of space explorers.

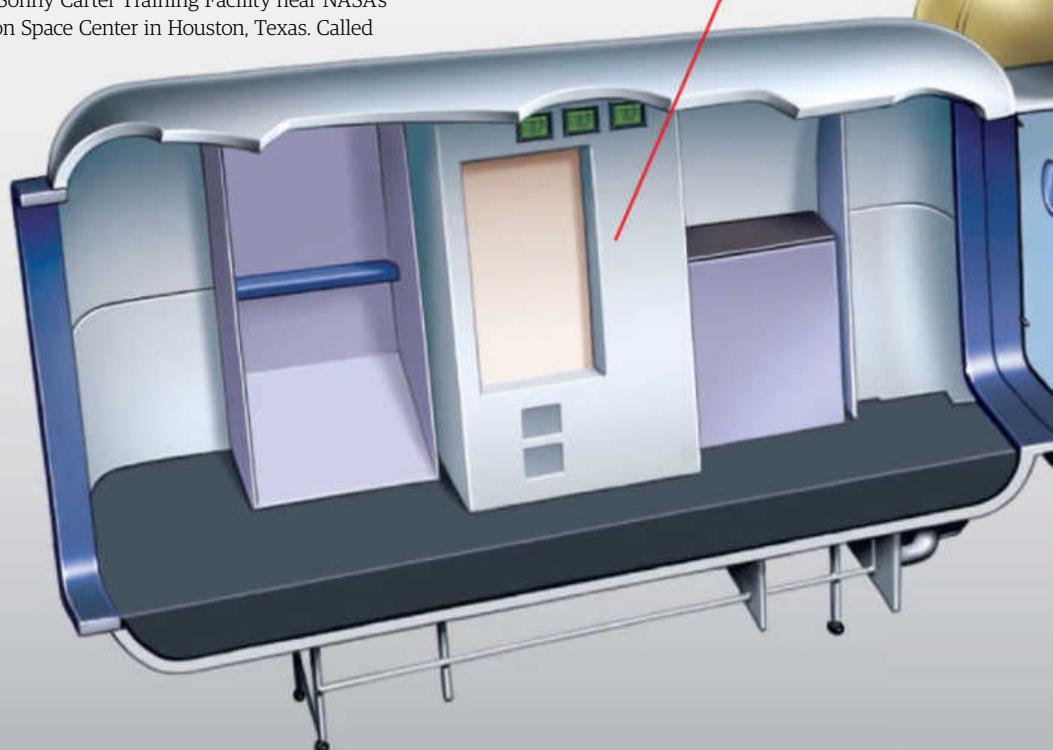
As well as using Aquarius, NASA has an enormous 22.7 million litre (6.2 million gallon) pool located at the Sonny Carter Training Facility near NASA's Johnson Space Center in Houston, Texas. Called

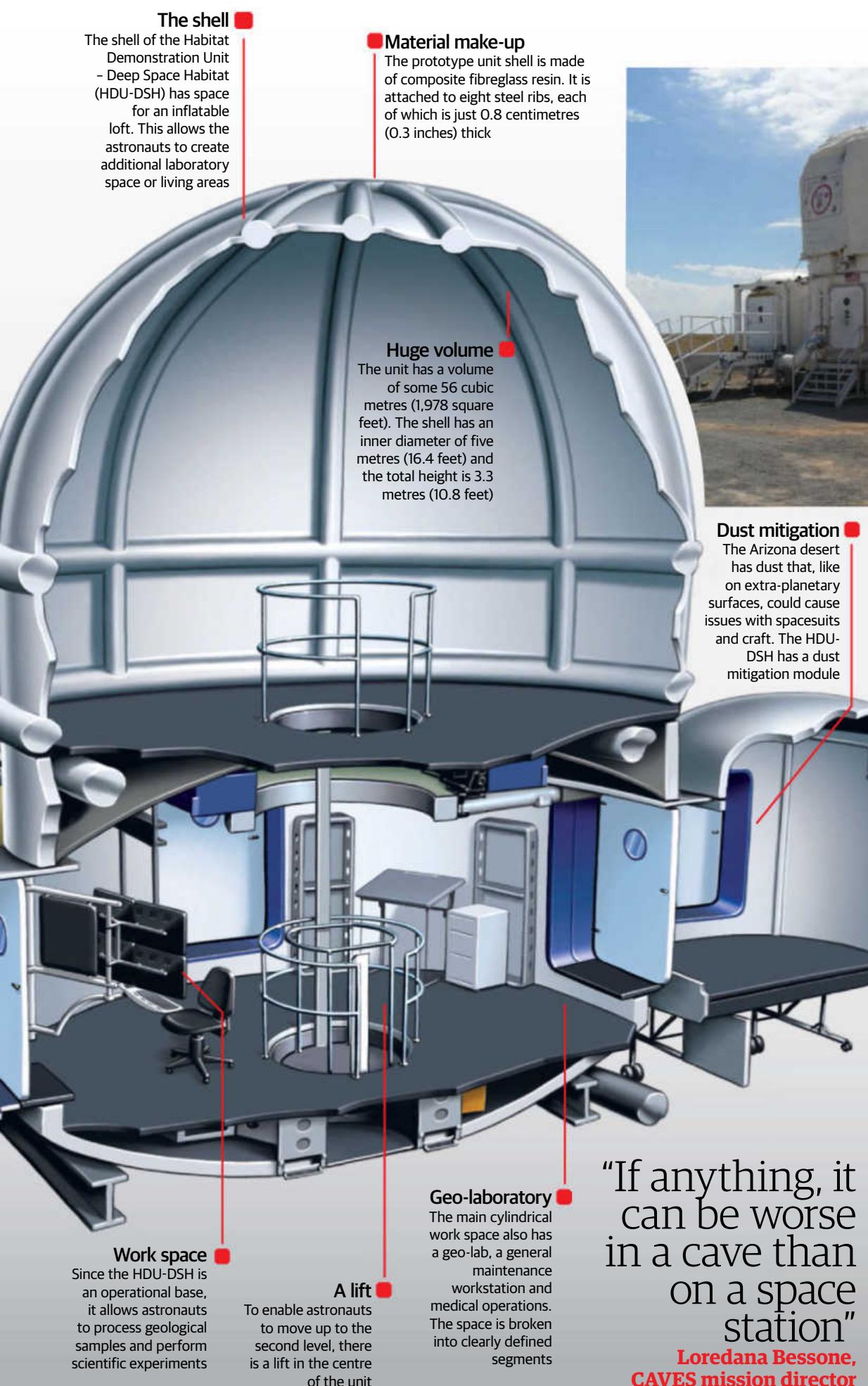
## The Deep Space Habitat

Analog research from Desert RATS (Desert Research and Technology Studies) enables NASA architects, engineers and scientists to create the perfect space base

### Analog research

This section is the HDU-DSH's hygiene module. It includes a toilet, sink and wet-bath area and it allows crews to monitor water usage rates and hygiene logistics of a two-person crew





## Desert RATS training

Located by a 2-million-year-old lava flow near Flagstaff, Arizona, Desert RATS conducts annual missions, with an emphasis on testing roving and spacewalks. They test for optimum crew sizes and the science that can be conducted on Mars, the Moon or other rocky bodies. It has experimented with backpacks and arm-mounted computers and it has introduced cutting edge robots. It has also experimented with surface networking and spacesuits that can use speech recognition to control suit parameters or the movement of robots. Any technology trialled one year is refined and tried again the next. The six-legged ATHLETE all-terrain vehicle has been chopped back to three legs, for example, and retested.

**"If anything, it can be worse in a cave than on a space station"**

**Loredana Bessone,  
CAVES mission director**





# Where in the world?

The training facilities across the globe that prepare astronauts for extra-terrestrial expeditions



## 1. Desert RATS Flagstaff, Arizona

Desert Research and Technology Studies (Desert RATS) makes use of the Black Point Lava Flow site in Arizona which shares a host of environmental and terrain similarities with Mars, the Moon and near-Earth asteroids. As well as understanding how rovers can cope with craters, slopes, dust storms and volcanic ash fields, it also looks at the tasks that would be better suited to humans such as sample collection.



## 2. In-Situ Resource Utilisation Mauna Kea, Hawaii

When astronauts in the future land on the Moon, they would, ideally, be able to produce their own oxygen from lunar rocks and soil. This dormant volcano has proven to be a perfect simulation of the Moon's polar regions. Scientists have studied the effectiveness of rovers to produce oxygen in such a harsh, dusty environment. It's a complex process so it's vital to be able to test the systems here on Earth first.



## 3. NEEMO Off the coast at Key Largo, Florida

Astronauts need to be prepared for a hostile, reduced-gravity environment and all of the risks that poses. NEEMO places six astronauts in isolation underwater. It assesses their physiology, psychology and nutrition and it teaches them the benefits of teamwork. Since the water constrains mobility, astronauts also get a good understanding of what an EVA on a planet or asteroid would be like.



#### 4. CAVES Sardinia, Italy

When astronauts perform EVAs on the International Space Station, they need to be able to operate while tethered and to carry out repairs, under pressure, in the dark and with limited visibility (as happened in December 2013 when a damaged cooling pump needed a repair). CAVES works on the leadership, decision-making, problem-solving and teamwork skills of cavingauts in isolated darkness.



#### 5. Mars 500 Russian Academy of Sciences' Institute of Biomedical Problems, Moscow, Russia

To send a human crew to Mars will take a long journey of some 245 days each way. With a few people in a confined space, it's important to protect their mental and physical health. Mars 500 simulated a 520-day Mars mission, giving three volunteer crews between 2007 and 2011 the opportunity to live and work in a mocked-up spacecraft.



#### 6. Haughton Mars Project Devon Island, Nunavut, Arctic Canada

Smart rovers, in particular, are useful for scouting sites before humans arrive and for collecting surface geology data. The remote isolation of the Haughton crater research station can help with the exploration of a Martian environment. Its unpredictable terrain is perfect for testing rovers and for astronauts: they can practice changing into a spacesuit from a pressurised vehicle while avoiding dust from entering.

**"The astronauts have to do body checks, remain attached to ropes and work together with their teammates"** **Loredana Bessone**

the Neutral Buoyancy Laboratory, it isn't a mission as such but a training exercise and yet it contains a mock-up of the International Space Station (ISS) modules and payloads and it allows for the simulation of weightlessness. Astronauts who intend to work on the ISS can familiarise themselves with the station's segments in an environment near identical to the real-life situation.

To simulate the weightless condition experienced during flight, astronauts need to maintain neutral buoyancy within the pool in order to avoid sinking or rising within the water. "This is the only way to experience weightlessness on the ground," says Stevenin. To do this, the astronaut's body must have an average density equal to the density of the fluid. It is achieved by adjusting the weight of the diving suit. By simulating microgravity and rehearsing spacewalks (or extra-vehicular activity (EVA) as they are known), the astronauts are able to experience some of the conditions they would experience when tending to the exterior of the ISS.

For the unimaginably cold temperature of space, the temperature at the Concordia Station in Antarctica can drop to -80 degrees Celsius (-112 degrees Fahrenheit). It is a useful analog for long duration deep space missions due to its confinement and extreme isolation. During the dark winters, the crew can be without hope of escape or deliveries for nine months. Scientists test for sleep disruption, telemedicine (medical advice via phone or internet), circadian rhythm and, thanks to the air pressure being equivalent to the top of Mount Fuji in Japan, chronic hypobaric hypoxia - a condition that arises from the body being deprived of sufficient oxygen.

As such, within each analog mission, small advances are invariably made, allowing plans to be revised and retested, with each meticulous detail noted so that scientific observations are at their most productive. The In-Situ Resource Utilisation (ISRU) analog mission in Mauna Kea, takes place at a dormant volcano in Hawaii, for instance. It has developed and tested mining equipment and production facilities to produce oxygen, fuel and water in-situ. The volcano helps to simulate the conditions of astronomical objects such as Mars and the Moon. It is hoped that, by introducing and examining new techniques, this analog mission will help reduce the amount of materials that need to be carried into space from Earth.

Analog missions are vital in this regard. Many of them put astronauts through challenging situations and by studying their behaviour and testing equipment or operational concepts, real-life missions can be refined for the benefit of the astronauts, research and productivity.

This is certainly true of ESA's CAVES (Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills). It is a two-week course which teaches astronauts to explore the Sa Grutta caves in Sardinia, Italy. The emphasis is on astronauts working as a multicultural crew in a

critical environment, re-creating spaceflight stressors while performing real scientific and exploration tasks.

Many of the procedures used underground are very similar to those on the ISS, with the same standards, formats and terminology. CAVES also trains astronauts to select samples and it assists them in the techniques of identifying the most important. For this reason, CAVES is quickly expanding, with the life science groups of NASA and ESA interested in conducting live science experiments that would accompany another major test site over at Pavilion Lake, British Columbia, Canada. This is a mission that not only lets astronauts assess microorganisms for their scientific value but allows for the testing of robot systems and pressurised underwater vehicles.

In fact, CAVES - which asks participants to live, work and explore in dark, cramped, isolated conditions deep underground - has been built as a combined environmental, scientific and operational analog to human space flight. "It's a very challenging analog mission especially because communication is only made available in selected locations with poor quality," says CAVES course and mission director Loredana Bessone. "The cavingauts cannot come back quickly to the surface either. It takes a few hours to reach the exit in nominal conditions."

For this reason cavingauts must use several techniques to develop situational awareness. They will very often stay close to the walls to orientate themselves. "The astronauts have to do body checks, remain attached to ropes and work together with their teammates," adds Bessone. "And it's a good analog, according to the participants who have been on the course and later flown in space flight. Many consider it to be one of the best if not the best analogs that they have ever been trained on."

Indeed, putting astronauts into such extreme environments can, as a consequence, help their development enormously. The Arizona-based mission Desert RATS (Desert Research and Technology Studies) simulates the operations of planetary exploration, exposing astronauts to the technologies and techniques that will protect them against the extreme environment of Mars or the Moon.

Desert RATS also looks at the possibility of humans one day occupying planets, moons and near-Earth asteroids. Habitats are trialled - the most recent being the HDU-DSH (Habitat Demonstration Unit - Deep Space Habitat) - that allow for crews to set up a longer-term base. Experiments are performed on these living and working quarters to ensure astronauts are comfortable, safe and able to carry out tasks while communicating with Earth-based crews.

Without the benefit of these kinds of analog missions - the likes of which have been conducted since the days of Apollo - space flight and exploration would be almost impossible. With them, astronauts, engineers and scientists are gaining new understanding, advancing science and coming up with new methods and technology. The future of human space exploration continues to look bright.



## Earth & Moon



# All About... THE MOON

The Moon is the Earth's only natural satellite, and the only celestial body that we've set foot on other than our own planet. But even though we know more about it than any other celestial body, the Moon continues to fascinate



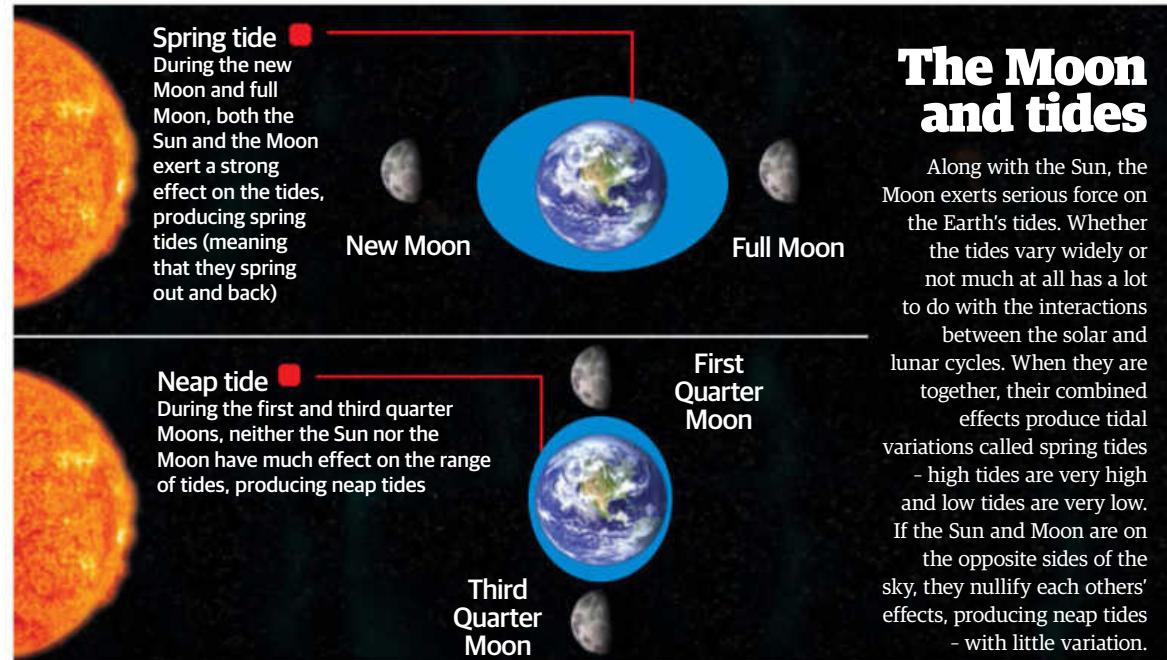
## Earth & Moon

Because we can easily discern features on the Moon with the naked eye, it has been a sense of wonder to us since ancient times. The Moon is the brightest object in our sky after the Sun, and influences everything from our oceans to our calendars. It's always been 'the Moon' because we didn't know that there were any others. Once Galileo discovered in 1610 that Jupiter had satellites, we've used the word 'moon' to describe celestial bodies that orbit larger bodies, which orbit stars. Since the Moon has always been so present, it might not seem worth studying. Yet there's a reason why we continue to return to it - we still have plenty to learn from our satellite.

The Moon is the fifth-largest and second-densest satellite in the Solar System. Its diameter is 27 per cent of Earth's at 3,476 kilometres (2,160 miles), while its mean density is 60 per cent that of the Earth's. This makes the Moon the largest satellite in size relative to the planet that it orbits. The Moon is also unusual because its orbit is more closely aligned to the plane of the ecliptic - the plane in which the Earth orbits. Most planetary satellites orbit closer to their planet's equatorial plane, but the Moon is inclined from the plane of the ecliptic by approximately 5.1 degrees.

Its average distance from the Earth is 384,400 kilometres (239,000 miles), and it completes an orbit once every 27.3 days. The Moon is in synchronous rotation with the Earth - its rotation and orbital period are the same - so the same side is almost always facing our planet. This is called the 'near side' of the Moon, while the opposite side is the 'far' or 'dark' side (although it gets illuminated just as often as the near side). This hasn't always been the case; the Moon used to rotate faster, but the influence of the Earth caused it to slow and become locked.

Although we say that we can only see one side of the Moon at a time,



## The Moon and tides

Along with the Sun, the Moon exerts serious force on the Earth's tides. Whether the tides vary widely or not much at all has a lot to do with the interactions between the solar and lunar cycles. When they are together, their combined effects produce tidal variations called spring tides - high tides are very high and low tides are very low. If the Sun and Moon are on the opposite sides of the sky, they nullify each other's effects, producing neap tides - with little variation.

**"The Moon is the fifth-largest and second-densest satellite in the Solar System. Its diameter is 27% of Earth's"**

that's not strictly true. The Moon's orbit isn't quite circular - it has an eccentricity of 0.0549. The Moon also wobbles a bit along its orbit. These two factors cause some variations in how much of the Moon that we see, called librations. When the Moon is closest to the Earth, called the perigee, it orbits slightly slower than it rotates. This means that we can actually get a glimpse of about eight degrees of longitude of its eastern far side. When the Moon is at its furthest point away in its orbit, the apogee, its orbit is slightly faster than its rotation. So we get a glimpse of eight degrees of longitude on its western far side. This is called longitudinal libration.

The Moon also appears to rotate towards and away from the Earth. This is due to the 5.1-degree inclination of its orbit, as well as the 1.5-degree tilt of the Moon's equator to the plane of the ecliptic. This results in us seeing about 6.5 degrees of latitude on the far side along both the sides of the poles. The Moon's orbit also means that it appears

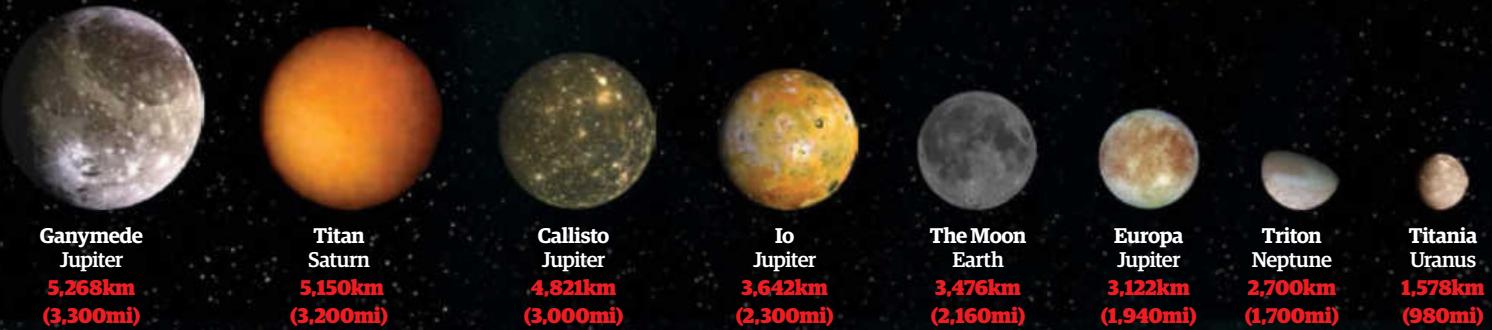
to move about 13 degrees across the sky each day, and this movement accounts for the lunar phases.

The Moon's gravitational pull has a strong effect on the Earth. The most obvious effect to us is the tides. High tide occurs when the level of water at the coastline rises, and low tide occurs when the water rushes further out. While some coastlines experience one high tide and one low tide per day, of equal strength, others have different strengths, timing and numbers of tides. Measuring and predicting these tides is incredibly important for everything from fishing to navigating intercoastal waterways. We use the term 'tides' to describe oceanic tides, but tides also occur on a smaller

level in lakes as well as the Earth's atmosphere and crust.

Scientists believe that the Moon formed when a huge celestial body about the size of Mars (which has been given the name Theia) impacted with a young Earth. This is known as the giant impact hypothesis. This force sent debris out into Earth's orbit, which fused to form the Moon. However, in 2012, an analysis of rock samples taken from the Moon during the Apollo missions showed that the Moon's composition is almost identical to Earth's. This calls the giant impact hypothesis into question, because previously we thought that at least some of the Moon's material had to have come from Theia.

## How the moons measure up



## The Moon's orbit

### Waxing gibbous

Between 51 and 99 per cent of the Moon is visible (right side in the north, left side in the south) in the later afternoon and most of the evening

### Full Moon

The entire Moon is visible all night long

### Waxing gibbous

Between 51 and 99 per cent of the Moon is visible (left side in the north, right side in the south) for most of the evening and in the early morning

### First quarter

Half of the Moon is visible (right side in the north, left side in the south) in the afternoon and early evening

### Waxing crescent

Up to 49 per cent of the Moon is visible (right side in the northern hemisphere, left side in the southern hemisphere) in the afternoon and after dusk

### New Moon

The first visible crescent in the southern hemisphere, seen after sunset

### Third quarter

Half of the Moon is visible (left side in the north, right side in the south) in the late evening and morning

### Waning crescent

Up to 49 per cent of the Moon is visible (left side in the north, right side in the south) just before dawn and in the morning

## Two sides of the Moon

As opposed to the near side, the far side is covered with craters and very little maria. This may be because it's hotter on that side, or because it experienced a collision

The near side of the Moon is mostly covered in dark areas that were originally thought to be seas, called maria (mare is singular). The lighter areas are called highlands



# The Moon inside and out

The Earth's only known satellite shares some remarkable similarities with our home planet

Although the Moon may seem like a solid rock, it's actually differentiated like the Earth; it has a core, a mantle and a crust. The Moon's structure likely came from the fractional crystallisation of a magma ocean that once covered the Moon. This probably happened not long after the Moon was formed, about 4.5 billion years ago. This means that as the magma ocean cooled, its composition changed as the different minerals within the melt crystallised into solids. The denser materials sank, forming the mantle, while less dense materials floated on top and formed the crust.

We believe that the core is probably very small, with a radius about 20 per cent the total size of the Moon. By contrast, most differentiated celestial bodies have cores about 50 per cent of their total size. The core itself comprises a solid innermost core that is rich in iron as well as nickel and sulphur, with a radius of 240 kilometres (150 miles). This

is surrounded by a fluid outer core, with about a 300-kilometre (186-mile) radius. Between the core and the mantle, there's a boundary layer of partially melted iron that has about a 500-kilometre (300-mile) radius. It is also known as the lower mantle. The upper mantle is mafic - rich in magnesium and iron, topped by a crust of igneous rock called anorthosite. It mainly includes the elements aluminium, calcium, iron, magnesium and oxygen, with traces of other minerals. We estimate the crust to be around 50 kilometres (31 miles) thick.

The Moon has no plate tectonics, but it does have seismic activity. When astronauts with the Apollo programme visited the Moon, they discovered that there are moonquakes - the Moon's equivalent of earthquakes. Moonquakes aren't nearly as strong as earthquakes, but they can last longer because there's no water to lessen the effects of the vibrations.

**"The Apollo astronauts discovered seismic activity on the Moon"**

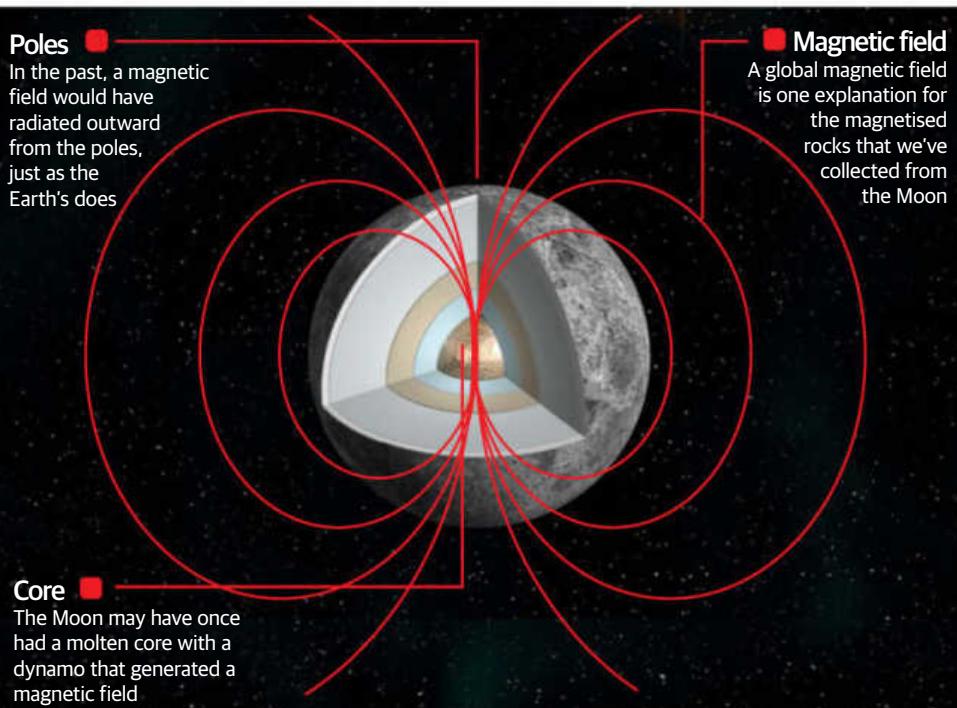
## The magnetic field mystery

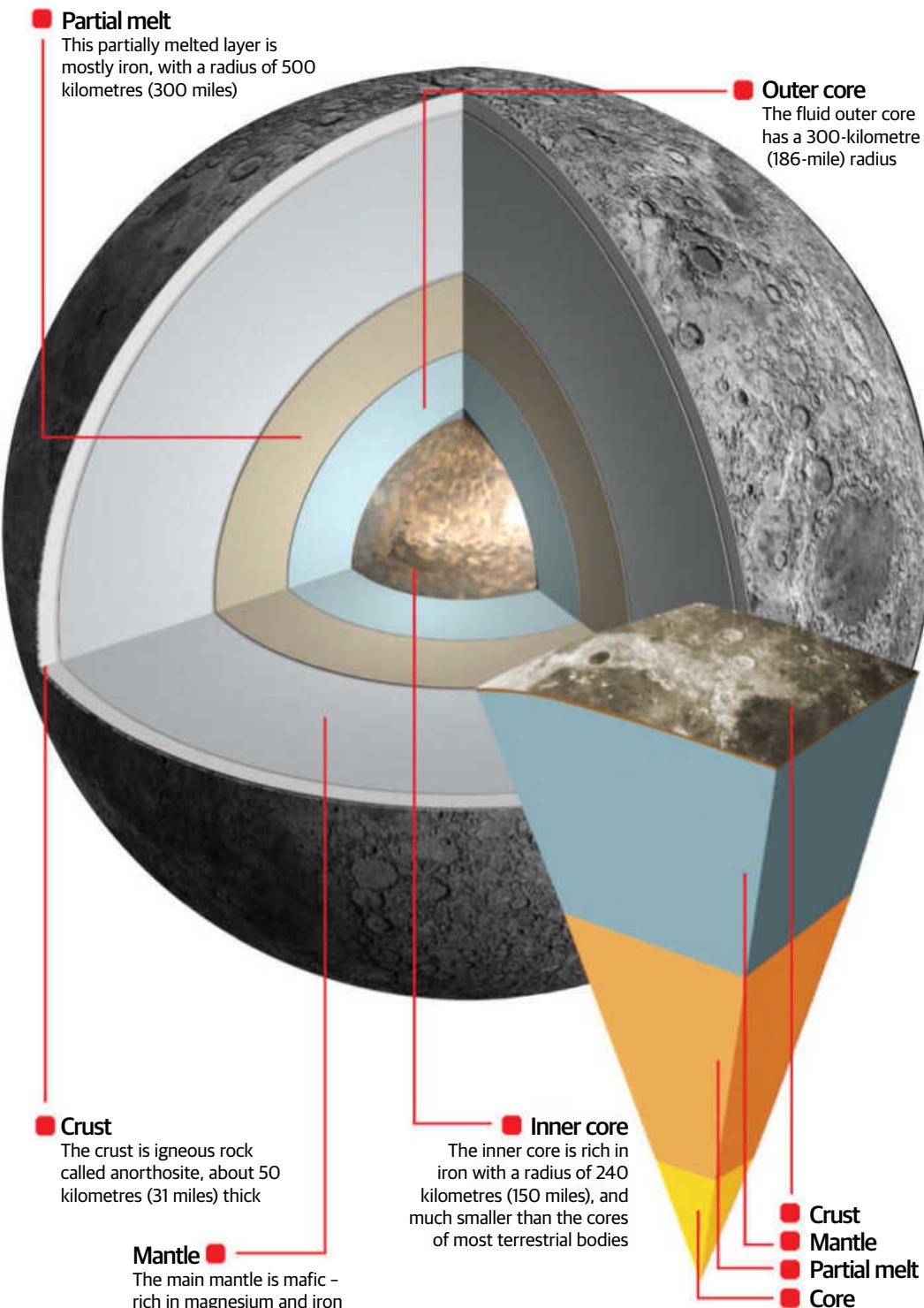
The Moon does have an external magnetic field - it's weak, less than one-hundredth that of the Earth's magnetic field. It's not a dipolar magnetic field like the Earth, which has a field that radiates outward from the north and south poles. So where did this magnetism come from? Researchers believe that the Moon once did have a dipole magnetic field, created by a dynamo - a convecting liquid core of molten metal. But we aren't sure what powered that dynamo. It could have worked like the Earth's dynamo. The Earth's dynamo powers itself, as elemental radioactive decay maintains convection in the core of our planet. The Moon could also have had a dynamo powered by the cooling of elements at the core. Yet if this were true, the magnetic field would have been completely gone about 4 billion years ago because the core is so small. Yet we have discovered magnetised lunar rocks that are younger than this. Another theory is that the Moon's dynamo was powered by the pull of the Earth's gravity when they were much closer together, or that impacts from large asteroids generated the magnetic field.

Seismometers placed by Apollo astronauts showed that the strongest moonquakes are about 5.5 on the Richter scale. There are four different types of moonquakes: shallow, deep, thermal and meteorite. Shallow ones occur just 20 kilometres (12 miles) below the surface, while deep moonquakes can be as deep as 700 kilometres (435 miles). These deep moonquakes are probably related to stresses on the Moon caused by its eccentric orbit and gravitational interactions between it and the Earth. Thermal earthquakes occur when the crust of the Moon heats and expands. This happens when the Moon is bathed in sunlight again after its two-week-long night. Finally, meteorites hitting the Moon can also cause a type of moonquake. However, shallow moonquakes are the strongest and most common. Nearly 30 of them were recorded between 1972 and 1977 by seismometers (turned off in 1977) that were left on the Moon's surface. This seismic data has helped us to determine the Moon's internal composition.

The dominating feature on the near side of the Moon's surface, called maria, are the result of ancient volcanic activity. These vast, dark plains are basalts - igneous rock that formed after lava erupted due to partial melting within the mantle. These basalts show that the Moon's mantle is much higher in iron than the Earth's, and has a varied composition. Some basalts are very high in titanium, while others are higher in minerals like olivine. For the most part, they flowed into impact basins.

These basalt maria have influenced the Moon's gravitational field because they're so rich in iron. The gravitational field contains mascons, big positive gravitational anomalies that influence how spacecraft orbit the Moon. They're also a bit of a mystery, however; the maria can't explain all of the mascons that have been tracked by the Doppler effect on the radio signals emitted by spacecraft that orbit the Moon. And there are also some large maria without associated mascons. ●





## The Moon in numbers

Fascinating facts and figures about Earth's only satellite

# 400

*How many times bigger the Sun is than the Moon. But it's also about 400 times further away from the Earth, which is why they look the same size in the sky*

# 29.5 days 12

*The length of a lunar month. It's longer than the amount of time it takes the Moon to orbit the Earth because the Earth is moving too*

The number of people who have actually set foot on the Moon

# 3.8cm (1.5in)

*The distance the Moon is moving away from the Earth each year*

# 13 hours

*The amount of time it takes to reach the Moon by rocket*

# 16.6kg (36.5lb)

*The amount you would weigh on the Moon if you weighed 100kg (220lb) on the Earth*

## How the Moon formed

**Impact**  
The giant impact theory posits that another body called Theia smashed into the Earth

**Ejection**  
Material from both Theia and the Earth was ejected into orbit around the planet

**Material orbit**  
The ejected material began to orbit in a mass

**Disc formation**  
As it travelled around the Earth, the material coalesced into a disc

**Moon**  
Eventually the disc formed into the spheroid that we know as the Moon



# On the surface

The surface of the Moon is about contrasts: light and dark, hot and cold

The landscape of the Moon is dominated by three main features: maria, terrae and craters. The basalt maria appear dark due to their high iron content and are much more prevalent on the near side of the Moon. Other volcanic features located on the surface of the Moon include domes and rilles. Domes are shield volcanoes that are round and wide with gentle slopes, while rilles are twisting sinuous formations caused by channels of flowing lava.

The lighter areas on the Moon are called terrae (terra is singular), or lunar highlands. They are made up of anorthosite, the type of igneous rock that dominates the overall crust of the Moon. While this type of rock can be located in some places on Earth, it's not generally found on the surface due to plate

tectonics and deposits. These highlands reflect light from the Sun and make it appear that the Moon is glowing at night.

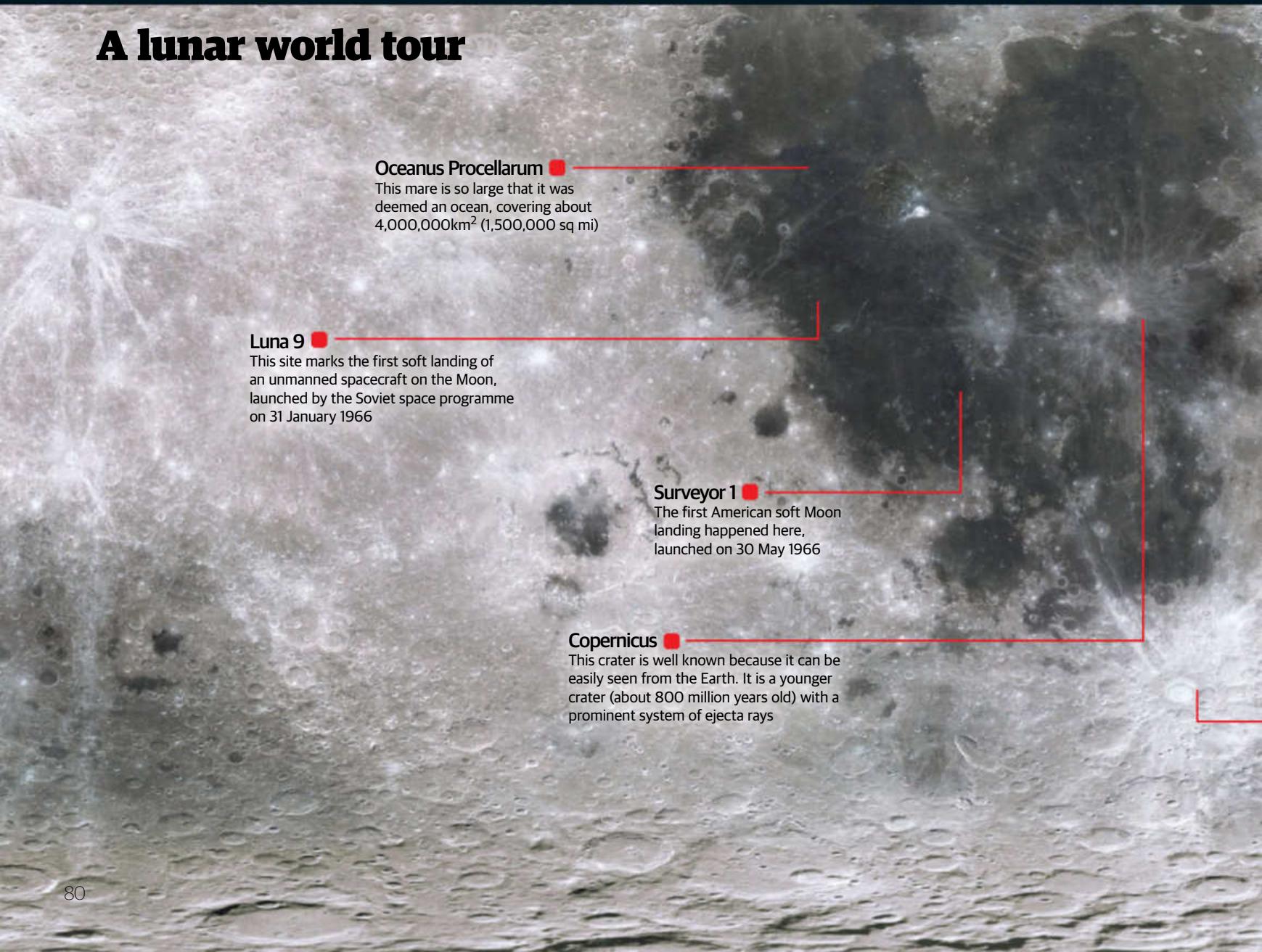
Both the maria and terrae have impact craters which were formed when asteroids and comets struck the surface of the Moon. These craters range in size from very tiny to massive. It is estimated that there are around 300,000 craters on the near side of the Moon that are wider than one kilometre (0.62 miles). The largest impact crater, called the South Pole-Aitken Basin, is about 2,500 kilometres (1,550 miles) in diameter and 13 kilometres (eight miles) deep. The biggest craters also tend to be the oldest, and many are covered in smaller craters. Younger craters have more sharply defined edges, while older

ones are often softer and rounder. If the impact was especially large, material may be ejected from the surface to form secondary craters.

In some cases, the basalt eruptions flowed into or over large impact craters called basins. In general, the terrae have far more craters, because the maria are younger in age than the terrae. While the Moon isn't much younger than the Earth, the Earth has processes that continue to change its surface over time, like erosion and plate tectonics. The Moon doesn't experience these, which is why some impact craters are up to 500 million years older than the basalt filling them.

The loose soil on the Moon is called regolith. It's powdery and filled with small rocks. Over time,

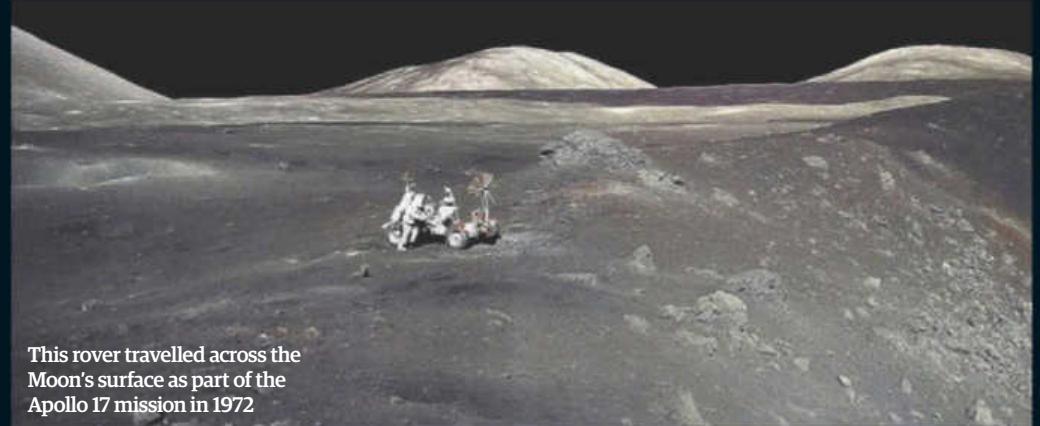
## A lunar world tour



impacts from meteors, as well as space weathering (solar wind, cosmic rays, meteorite bombardment and other processes), break down the rocks and grind them into dust. Aside from the basalt and anorthosite rocks, there are also impact breccias - rock fragments that were welded together by meteor impacts - and glass globules from volcanic activity.

Although you may see the term 'lunar atmosphere' used in some places, the Moon is actually considered to exist in a vacuum. There are particles suspended above the surface, but the density of the Moon's atmosphere is less than one hundred trillionth that of the Earth's atmosphere. What little atmosphere there is gets quickly lost to outer space, and is constantly replenished. Two processes help to replenish the Moon's atmosphere: sputtering and outgassing. Sputtering occurs when sunlight, solar wind and meteors bombard the surface and eject particles. Outgassing comes from the radioactive decay of minerals in the crust and mantles, which can release gases like radon.

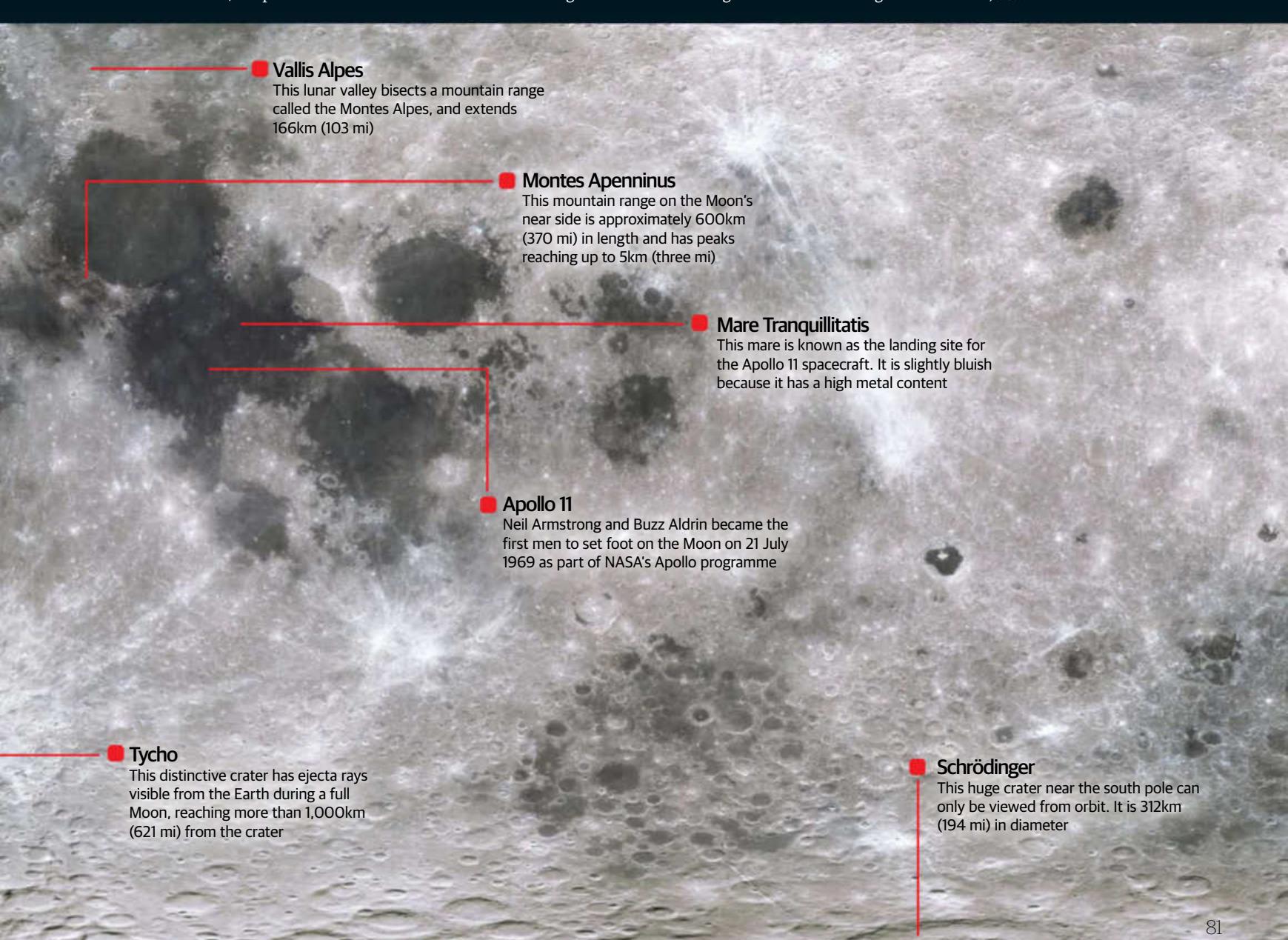
The Moon has a very minor axial tilt, so there aren't seasons in the same way that we have them here on Earth. However, temperatures on the



This rover travelled across the Moon's surface as part of the Apollo 17 mission in 1972

Moon can change dramatically because there's no atmosphere to trap heat, and portions of the Moon may be either in full sunlight or total darkness depending on where it is in its rotation. Full sunlight can mean temperatures of greater than 100 degrees Celsius (212 degrees Fahrenheit). But at the end of the lunar day, the temperature can drop by hundreds of degrees. There are also big differences

in temperatures depending on the surface features. For example, the Moon is coldest in its deepest craters, which always remain in darkness. The coldest temperature ever recorded in the Solar System by a spacecraft was measured by the Lunar Reconnaissance Orbiter in the Hermite Crater near the Moon's north pole at -248 degrees Celsius (-414 degrees Fahrenheit).



#### Vallis Alpes

This lunar valley bisects a mountain range called the Montes Alpes, and extends 166km (103 mi)

#### Montes Apenninus

This mountain range on the Moon's near side is approximately 600km (370 mi) in length and has peaks reaching up to 5km (three mi)

#### Mare Tranquillitatis

This mare is known as the landing site for the Apollo 11 spacecraft. It is slightly bluish because it has a high metal content

#### Apollo 11

Neil Armstrong and Buzz Aldrin became the first men to set foot on the Moon on 21 July 1969 as part of NASA's Apollo programme

#### Tycho

This distinctive crater has ejecta rays visible from the Earth during a full Moon, reaching more than 1,000km (621 mi) from the crater

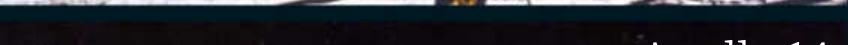
#### Schrödinger

This huge crater near the south pole can only be viewed from orbit. It is 312km (194 mi) in diameter



## Earth & Moon

Apollo 11



Apollo 14



Apollo 12

# Exploring the Moon: the past

### **Apollo 11** 21 July 1969

NASA astronauts Buzz Aldrin and Neil Armstrong became the first humans to set foot on another body in space when they landed on the Moon in 1969. This mission ended the race to the Moon between the United States and the USSR.

### **Apollo 12** 19 November 1969

The second spacecraft to land on the Moon, Apollo 12 used a Doppler effect radar technique to precisely land the spacecraft within walking distance of the Surveyor 3 probe, which had landed on the lunar surface about two years prior.

### **Apollo 14** 5 February 1971

The commander on board the third spacecraft to land on the Moon was Alan Shepard, who, a decade earlier on 5 May 1961, had become the second person in space after Yuri Gagarin and the first American as part of the Mercury programme.

### **Apollo 15** 30 July 1971

NASA deemed this Moon landing the most successful so far out of its manned missions. It is also known as the first of the longer missions to the Moon, called 'J missions', staying for three days.

### **Apollo 16** 21 April 1972

Apollo 16 became the first spacecraft to land in the highlands on the Moon, which let them gather older lunar rocks. The astronauts also spent about three days on the surface.

### **Apollo 17** 11 December 1972

This last manned mission to the Moon was the only one to carry the Traverse Gravimeter Experiment (TGE) that measured relative gravity at different sites on the Moon.

### **Luna 1** 4 January 1959

This Soviet probe was the first to reach the vicinity of the Moon and the first to break out of geocentric orbit, however, it did not actually impact the Moon as had originally been planned.

### **Luna 21** 15 January 1973

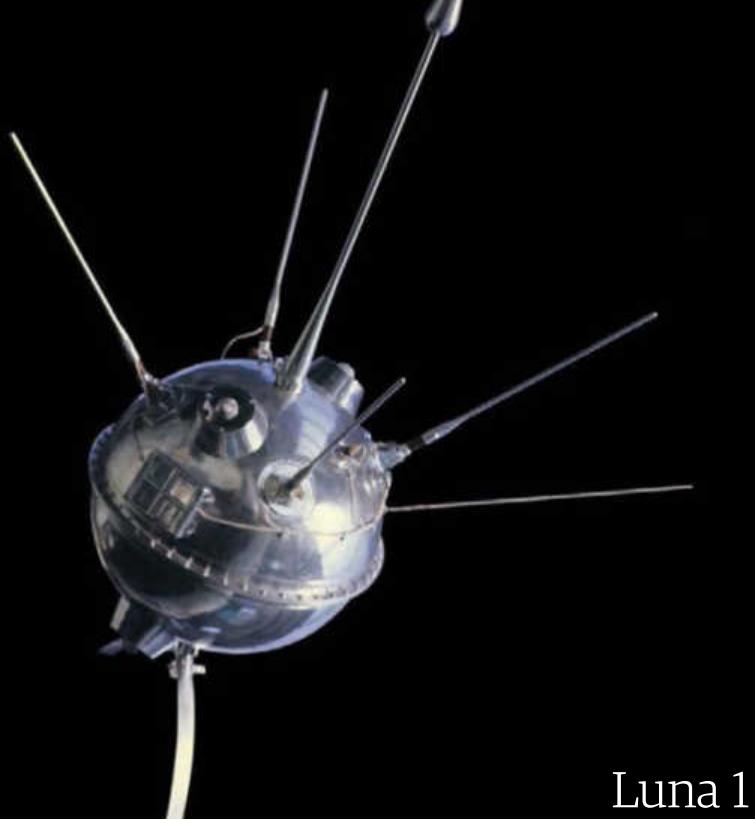
This Soviet spacecraft landed on the Moon and carried a lunar rover, Lunokhod 2. It performed numerous experiments and sent back more than 80,000 images before failing.

### **Luna 24** 22 August 1976

This was the last of the Luna missions, successfully landing near Mare Crisium to recover samples. It remains the last spacecraft to have a soft landing on the Moon's surface.

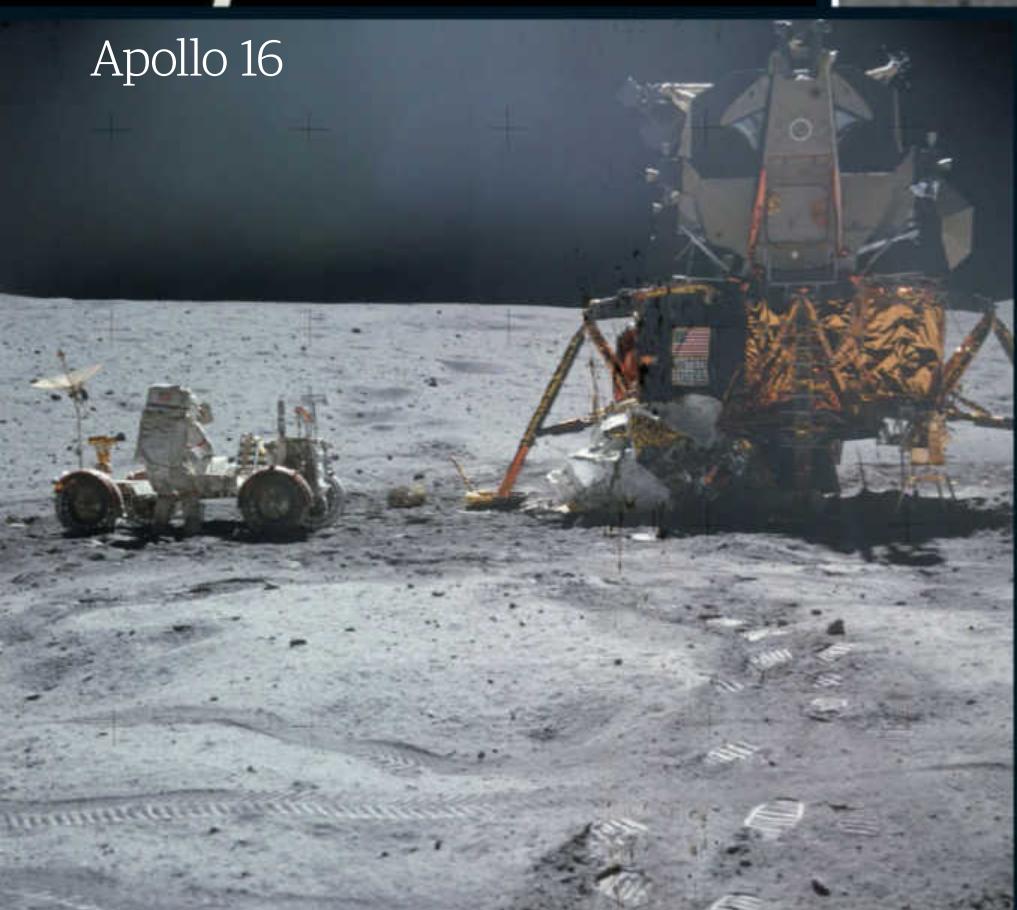
Apollo 15



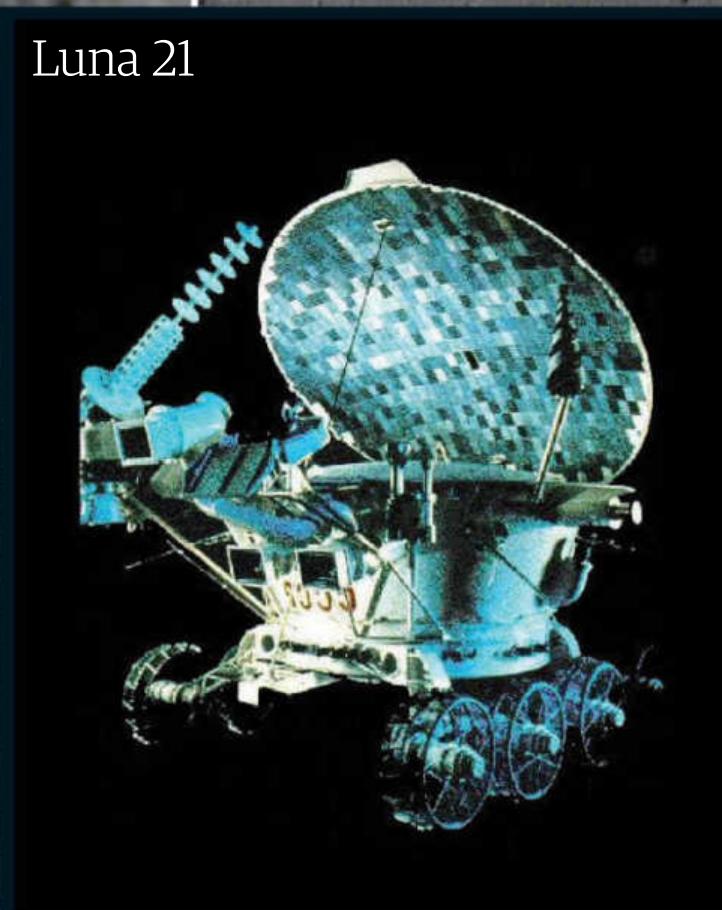


Luna 1

Luna 24



Apollo 16



Luna 21



Apollo 17



# Exploring the Moon: present and future

We've been studying the Moon for over 50 years, and thanks to a host of pioneering missions we now know more about our satellite than ever before

Although there hasn't been a manned mission to the Moon since 1972 and there were no soft landings at all until 1966, we're still exploring our satellite. Currently the Lunar Reconnaissance Orbiter (LRO) is still circling the Moon. It launched on 18 June 2009, and became the first NASA mission to the Moon in more than a decade. The LRO is meant



The image taken by the Lunar Reconnaissance Orbiter shows the Apollo 11 landing site, including the astronauts' footprints, landing module and discarded tools

to be a precursor to future manned missions, and was originally designed to spend just a year in orbit. However, the mission was extended several times. It was designed to extensively map the Moon in high resolution, explore the potential of ice in the polar regions, study the deep space radiation, and continue to map the surface of the Moon. The other current NASA mission is ARTEMIS, an extension of an earlier satellite mission. Two small probes have been orbiting the Moon together since summer 2011, having previously performed lunar and Earth flybys.

The Lunar Crater Observation and Sensing Satellite (LCROSS) was launched along with the LRO and considered an inexpensive way to look for water ice, and it was successful. The LCROSS discovered ice in the Cabeus crater near the Moon's south pole after its upper stage impacted as planned on 9 October 2009. Two small spacecraft under the name GRAIL A and GRAIL B were launched on 10 September 2011 and impacted on 17 December 2012, having collected data to help understand how terrestrial planets have evolved. Japan, India and China have all had lunar probes in the last six years as well. Currently there are several proposed lunar missions on the table for launch within the next few years, coming from the United States, China, Russia and India. ■

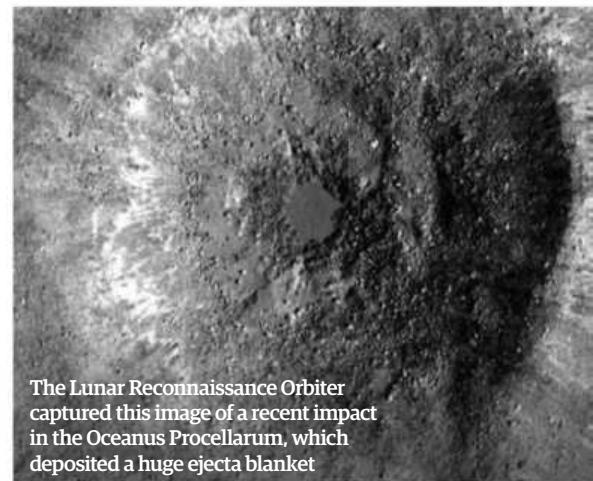
**"It was designed to extensively map the Moon in high resolution"**



This Lunar Reconnaissance Orbiter image shows the landing site of the Apollo 17 spacecraft, including the lunar rover



Buzz Aldrin and Neil Armstrong became the first humans to walk on the Moon in 1969



The Lunar Reconnaissance Orbiter captured this image of a recent impact in the Oceanus Procellarum, which deposited a huge ejecta blanket

## Current and future missions

### Luna-Glob Russia



This Russian Federal Space Agency programme is scheduled to be the first of a series of missions, with the ultimate goal of creating a robotic base on the Moon. Its goals include gathering seismic activity, studying cosmic rays, and studying the origin of the Moon.

### Chang'e 2 China



This Chinese probe was launched on 1 October 2010 and left lunar orbit in November to go on an extended mission. Chang'e 2 was designed to study future landing sites.



### Kaguya Japan

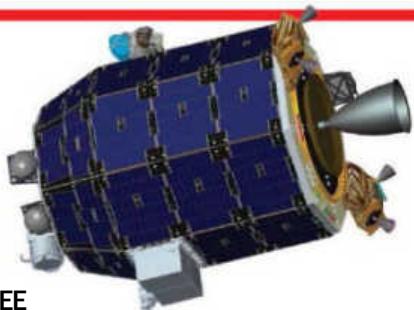
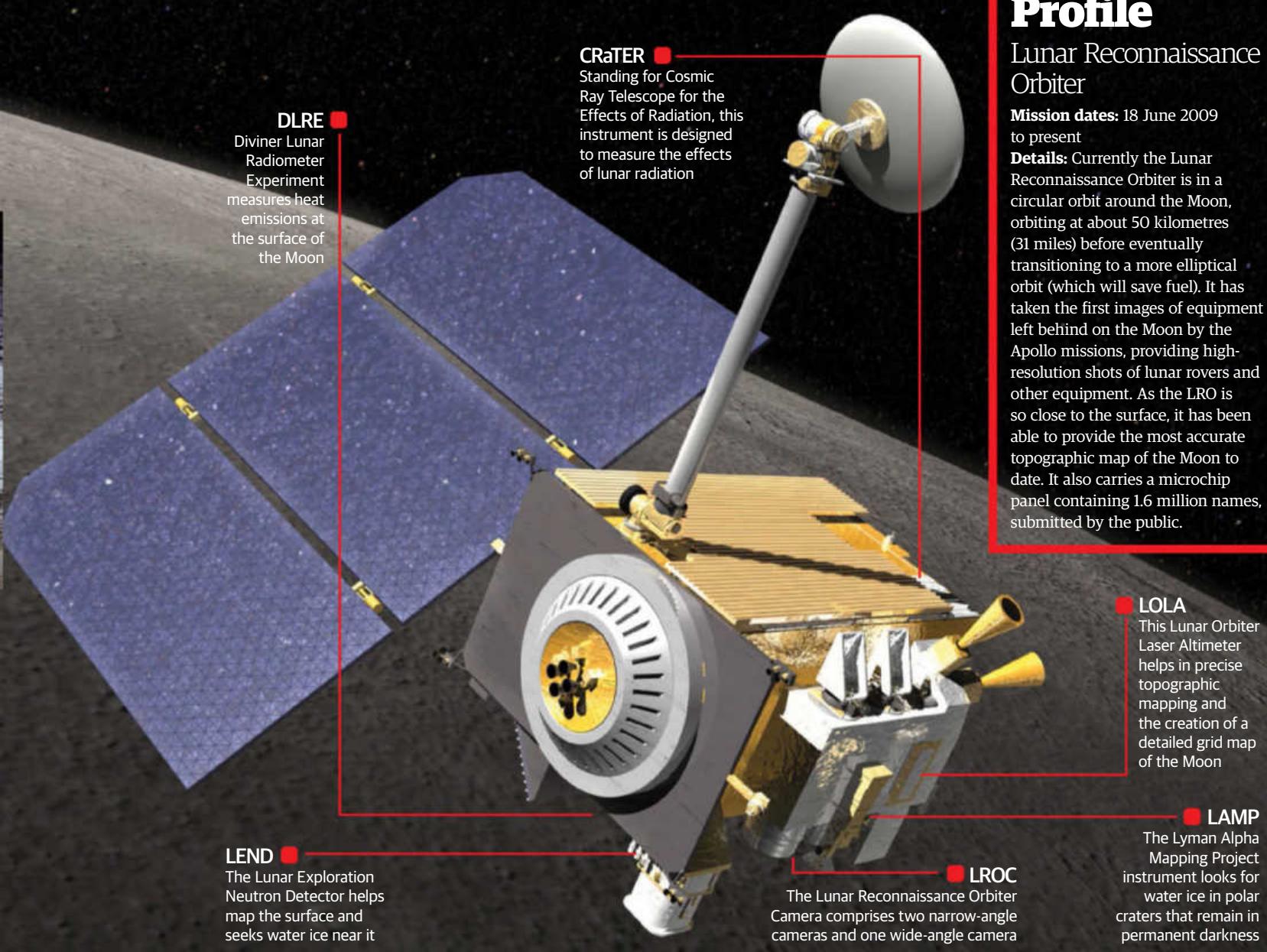
Also known as SELENE, this Japanese orbiter was launched on 14 September 2007 and circled the Moon before impacting on 10 June 2009. Kaguya measured the Moon's gravity, studied the surface and sought information on the Moon's history.

## Mission Profile

Lunar Reconnaissance Orbiter

**Mission dates:** 18 June 2009 to present

**Details:** Currently the Lunar Reconnaissance Orbiter is in a circular orbit around the Moon, orbiting at about 50 kilometres (31 miles) before eventually transitioning to a more elliptical orbit (which will save fuel). It has taken the first images of equipment left behind on the Moon by the Apollo missions, providing high-resolution shots of lunar rovers and other equipment. As the LRO is so close to the surface, it has been able to provide the most accurate topographic map of the Moon to date. It also carries a microchip panel containing 1.6 million names, submitted by the public.



**LADEE**  
USA

NASA plans to launch the Lunar Atmosphere and Dust Environment Explorer (LADEE) in August 2013. It hopes to learn more about the lunar atmosphere before there are more manned missions, including the dust on the Moon's surface.



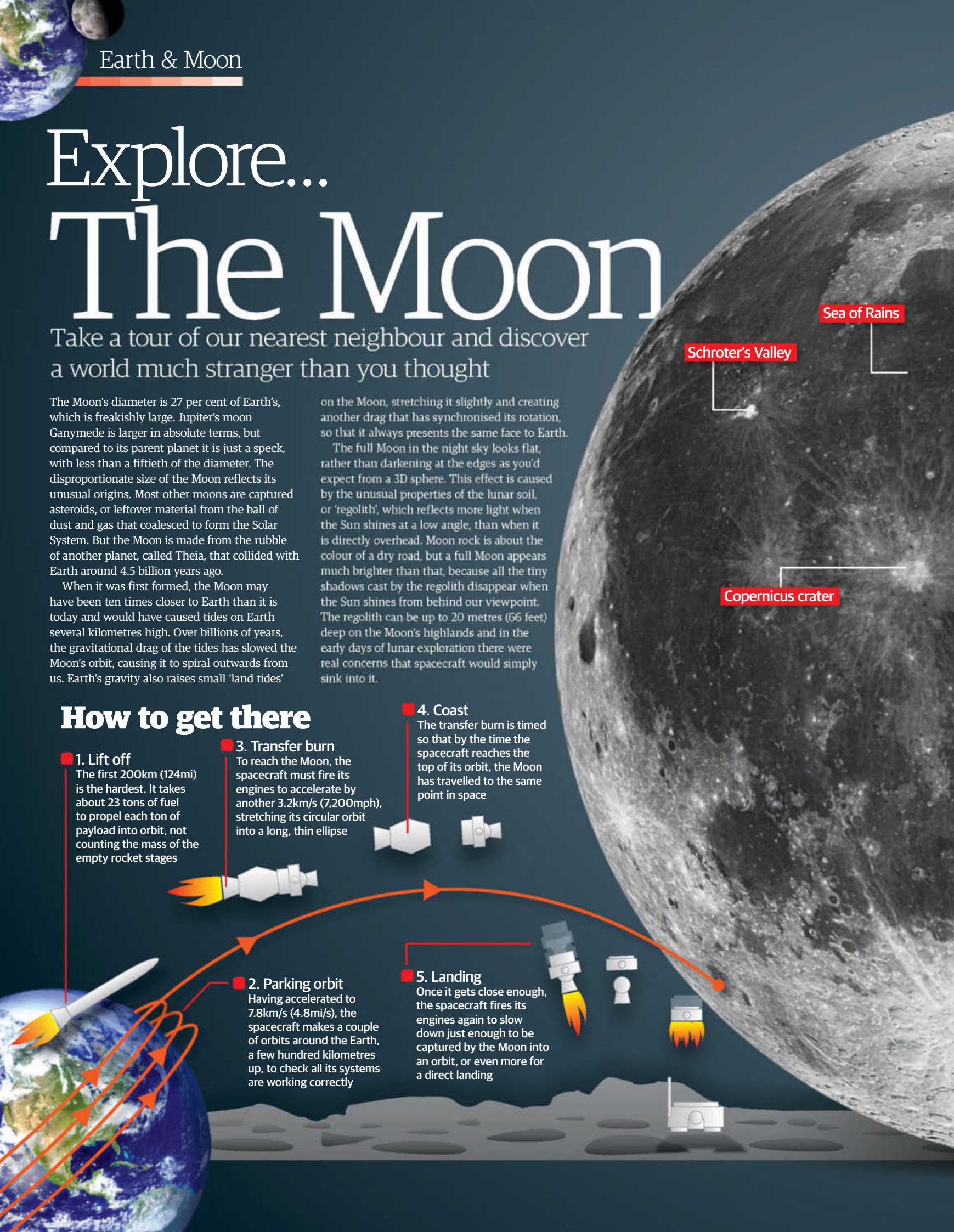
**Lunar Mission One**  
UK

This UK-led mission – funded by private donations – hopes to survey the South Pole of the moon, an area that's previously remained unexplored. With an aim to drill down at least ten metres, but possibly 100, they hope to learn more about Earth's satellite.



**Chandrayaan-1**  
India

This was India's very first unmanned space probe. It launched on 22 October 2008 and the mission ended on 29 August 2009. It launched an impact probe that planted an Indian flag on the south pole, making it the fourth country to place a flag on the Moon.



# Explore... The Moon

Take a tour of our nearest neighbour and discover a world much stranger than you thought

The Moon's diameter is 27 per cent of Earth's, which is freakishly large. Jupiter's moon Ganymede is larger in absolute terms, but compared to its parent planet it is just a speck, with less than a fiftieth of the diameter. The disproportionate size of the Moon reflects its unusual origins. Most other moons are captured asteroids, or leftover material from the ball of dust and gas that coalesced to form the Solar System. But the Moon is made from the rubble of another planet, called Theia, that collided with Earth around 4.5 billion years ago.

When it was first formed, the Moon may have been ten times closer to Earth than it is today and would have caused tides on Earth several kilometres high. Over billions of years, the gravitational drag of the tides has slowed the Moon's orbit, causing it to spiral outwards from us. Earth's gravity also raises small 'land tides'

on the Moon, stretching it slightly and creating another drag that has synchronised its rotation, so that it always presents the same face to Earth.

The full Moon in the night sky looks flat, rather than darkening at the edges as you'd expect from a 3D sphere. This effect is caused by the unusual properties of the lunar soil, or 'regolith', which reflects more light when the Sun shines at a low angle, than when it is directly overhead. Moon rock is about the colour of a dry road, but a full Moon appears much brighter than that, because all the tiny shadows cast by the regolith disappear when the Sun shines from behind our viewpoint. The regolith can be up to 20 metres (66 feet) deep on the Moon's highlands and in the early days of lunar exploration there were real concerns that spacecraft would simply sink into it.

## How to get there

### 1. Lift off

The first 200km (124mi) is the hardest. It takes about 23 tons of fuel to propel each ton of payload into orbit, not counting the mass of the empty rocket stages

### 3. Transfer burn

To reach the Moon, the spacecraft must fire its engines to accelerate by another 3.2km/s (7,200mph), stretching its circular orbit into a long, thin ellipse

### 4. Coast

The transfer burn is timed so that by the time the spacecraft reaches the top of its orbit, the Moon has travelled to the same point in space

### 2. Parking orbit

Having accelerated to 7.8km/s (4.8mi/s), the spacecraft makes a couple of orbits around the Earth, a few hundred kilometres up, to check all its systems are working correctly

### 5. Landing

Once it gets close enough, the spacecraft fires its engines again to slow down just enough to be captured by the Moon into an orbit, or even more for a direct landing



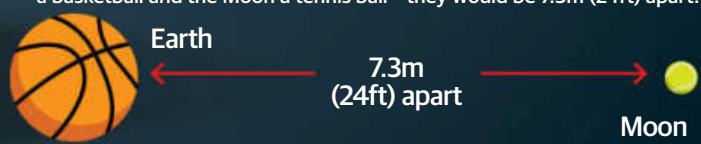
## How big is the Moon?

The Moon is the fifth largest satellite in the Solar System and the biggest in comparison to its host planet



## Distance from Earth

The Moon is currently 384,400km (238,855mi) away from Earth but is gradually moving away at a rate of 3.82cm (1.5in) a year. If the Earth was a basketball and the Moon a tennis ball - they would be 7.3m (24ft) apart.





# Top sights to see on the Moon

Seen from Earth, the most obvious features on the Moon are the 'maria' or seas. These are vast plains of solidified lava that originally bled for tens of millions of years from the puncture wounds of asteroid impacts. They are darker than the rest of the Moon's crust because of the iron compounds in the basalt minerals. The Moon long ago cooled and set solid all the way through, so it doesn't have tectonic plates to throw up mountain ranges like Earth's. But asteroid impacts can do the same job in a fraction of the time. Large impacts create mountain ridges around their rims, such as the Montes Rook which form a ring 500 kilometres (310 miles) wide around the Mare Orientale. Where an impact crater hasn't been filled in by lava to form a mare, there is also a central

mountain formed where the crust rebounded from the initial impact. Impacts can fling debris out over hundreds of kilometres. These form spokes of lighter asteroid material overlaid on the darker lunar regolith. Tycho crater in the southern hemisphere has rays that extend 1,500 kilometres (930 miles) from its rim.

When the Soviet Union sent Luna 3 to photograph the far side of the Moon for the first time, in 1959, they found it strangely lacking in maria. This is because the crust is thicker on the far side, so asteroid impacts didn't punch all the way through to the magma beneath. Instead the terrain is more irregular, thrust into a jumble of spires by the shockwaves from ancient impacts on the opposite side that travelled through the Moon and burst out

### Copernicus crater

A relatively young crater at just 800 million years old. The mountains in the centre are almost as high as Ben Nevis.



### Apollo 11 landing site

Chosen because it was fairly flat, Neil Armstrong nevertheless had to manually pilot 6km (3.7mi) from the intended landing site to avoid a boulder field.

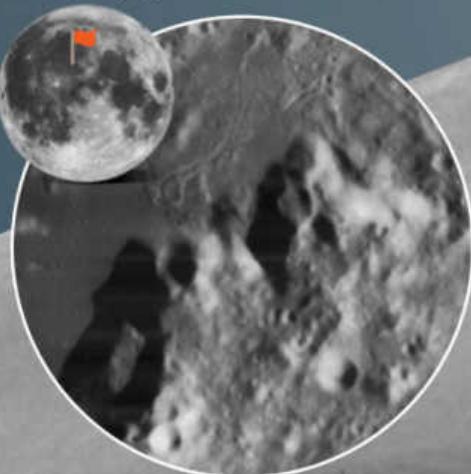


of the surface, like an exit wound. Without water or wind, the landscape is unweathered, so every mountain is sharp and jagged.

As well as mountains and craters, the Moon has twisting features that look like river valleys. Called 'rilles', these may have been caused by lava tubes that cooled and sank into the regolith. Hadley Rille, where Apollo 15 landed, runs along the base of the Apennine mountains. Schröter's Valley is the largest lunar rille. It begins at a crater six kilometres (3.7 miles) wide and meanders for hundreds of kilometres in a strip that is ten kilometres (6.2 miles) wide in places. In fact it's so big that it has another smaller rille formed by a second lava flow, running along it like a river meandering through a glacial valley.

### Tallest lunar mountain

Mons Huygens is part of the rim of the vast crater that filled with lava to become the Sea of Rains. It is 5.5km (3.4mi) high.



### Apollo 17 landing site

The last human footprints on the Moon were left by Eugene Cernan, the commander of Apollo 17, as he climbed back aboard in December 1972.



## The lunar orbit explained

The Moon spins on its axis at the same speed as it rotates around the Earth. This 'tidal locking' means a day on the Moon lasts almost four weeks. As the day/night terminator creeps slowly across the surface, we see a different phase illuminated in the sky each night, from new Moon to full Moon and back again.

### The Moon's orbit is oval shaped

■ Perigee  
363,400km/225,800mi (distance when closest to Earth)



Apogee  
405,500km/252,000mi (distance when farthest to Earth)

■ 16km/h (10mph)  
Speed of the Moon's rotation

■ 3,700km/h (2,300mph)  
Speed of the Moon orbiting Earth

New Moon

Waxing Crescent Moon

Waxing Crescent Moon

Last Quarter Half Moon



Waxing Gibbous Moon

Full Moon

First Quarter Half Moon

Waxing Gibbous Moon

## The Moon in numbers



1,738km  
*Radius of the Moon - just over a quarter of Earth's*

# 0.1654g

Surface gravity on the Moon,  
where you'd be a sixth your Earth weight

### Weather forecast

100°C  
-153°C



The Moon has virtually no atmosphere, just a sprinkling of evaporating atoms. So there is no wind to create weather systems. In direct sunlight the ground heats to over 100°C (212°F) but in the shade of a crater it can be as low as -247°C (-413°F).

1972  
*The last time anyone stepped foot on the Moon*

30%  
*Increase in brightness of the Moon when closest to Earth*

135days  
*to get to the Moon by car travelling at 70mph*



*Hours in a lunar day, sunrise to sunrise*

# Beyond Earth

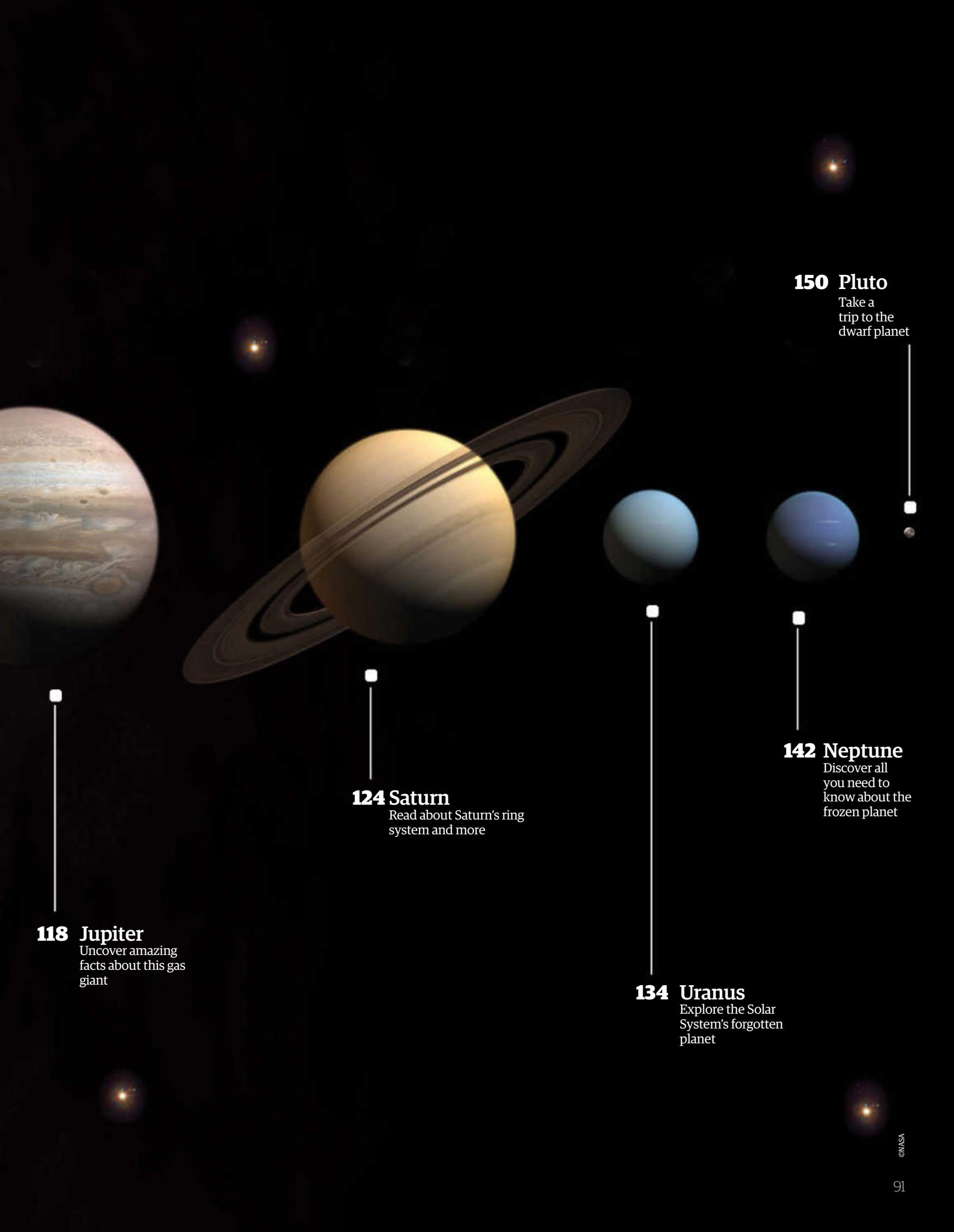
Explore the planets that neighbour  
Earth within our Solar System

**92 Mercury**  
Learn about the  
planet closest to  
the Sun

**100 Venus**  
Explore the Earth's twin planet

Earth

**110 Mars**  
Learn how  
to survive on  
the Red Planet



## **118** Jupiter

Uncover amazing facts about this gas giant

## **124** Saturn

Read about Saturn's ring system and more

## **134** Uranus

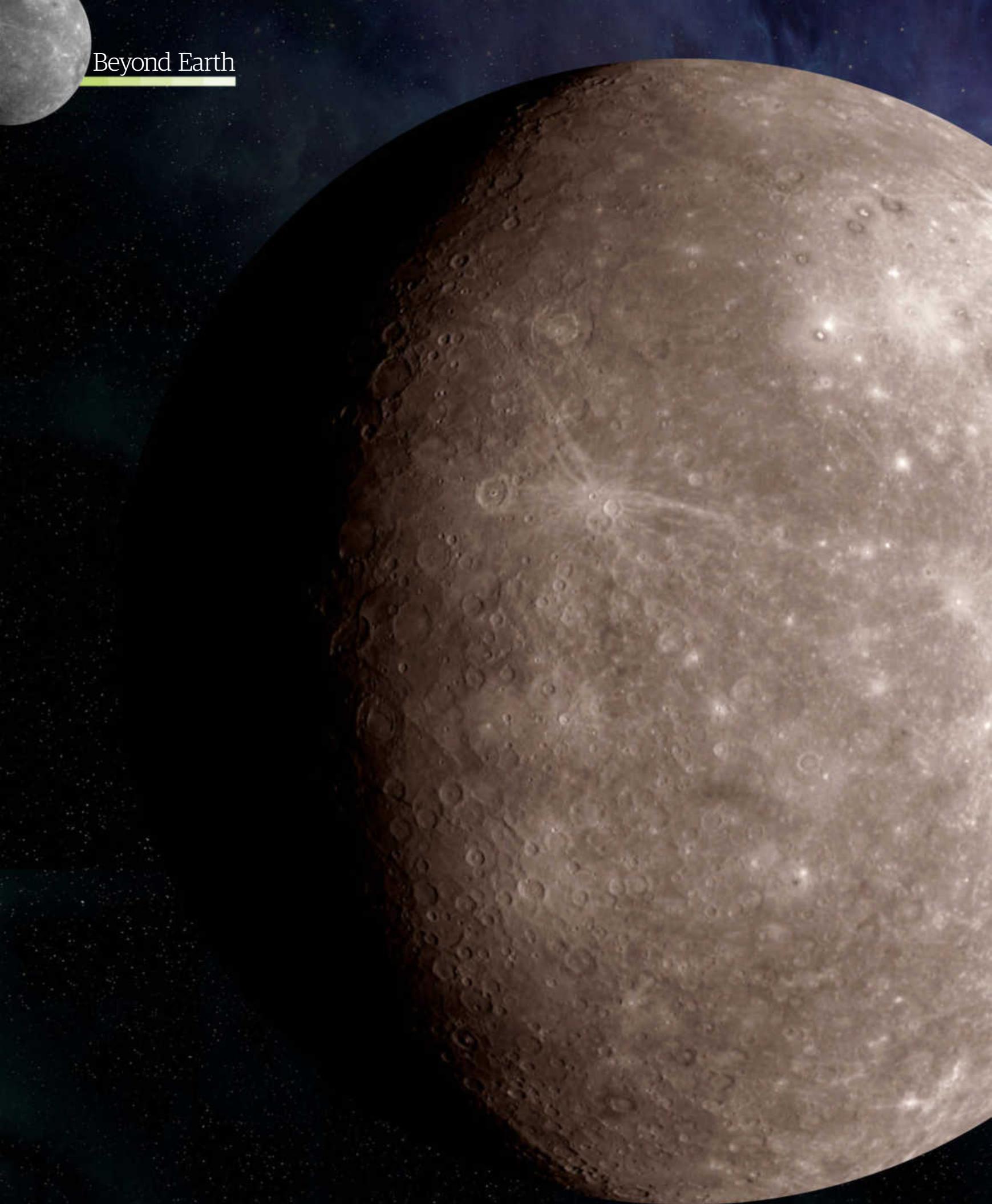
Explore the Solar System's forgotten planet

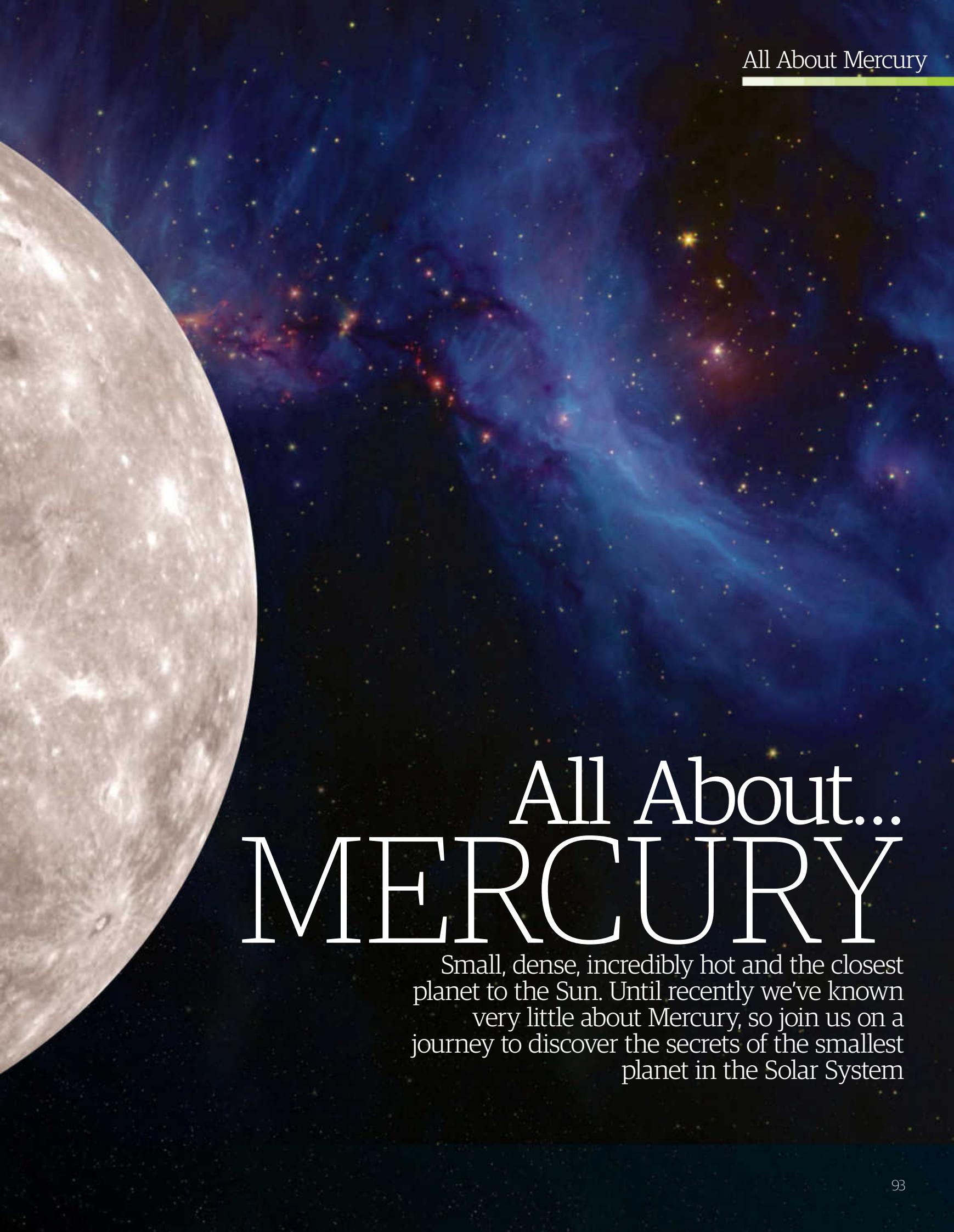
## **142** Neptune

Discover all you need to know about the frozen planet

## **150** Pluto

Take a trip to the dwarf planet





# All About... MERCURY

Small, dense, incredibly hot and the closest planet to the Sun. Until recently we've known very little about Mercury, so join us on a journey to discover the secrets of the smallest planet in the Solar System

Every planet is unique, but Mercury is a planet of paradoxes and extremes, and that's just based on what we know so far. It's the innermost planet, the smallest planet and has the most eccentric orbit. We've known about its existence since the third millennium BC, when the Sumerians wrote about it. But they thought that it was two separate planets - a morning star and an evening star - because that's just about the only time you can see it due to its closeness to the Sun. The Greeks knew it was just one planet, and even that it orbited the Sun (long before acknowledging that the Earth did, too). Galileo could see Mercury with his telescope, but couldn't observe much.

This little planet has a diameter that's 38 per cent that of Earth's diameter - a little less than three Mercurys could fit side by side Earth. It has a diameter of about 4,880 kilometres (3,032 miles). There are two moons in the Solar System that are bigger than Mercury, but the Earth's Moon is only about a 1,000 kilometres (621 miles) smaller. In surface area,

it's about ten per cent that of Earth (75 million square kilometres or 29 million square miles), or about twice the size of Asia if you could flatten it out. Finally, in volume and mass Mercury is about five per cent that of Earth. Volume-wise that means that 18 Mercurys could fit inside one Earth. While it's small, it's incredibly dense; almost on par with Earth's density due to its heavy iron content.

Mercury is odd in other ways, too. It's tilted on its axis just like Earth (and all the planets in the Solar System), but its axial tilt is only 2.11 degrees away from the plane of the ecliptic. Contrast that with the Earth's tilt at 23.4 degrees. While that causes the Earth's seasons, Mercury has no seasons at all. It's simple - the side that faces the Sun is incredibly hot, and the side away from the Sun is incredibly cold. There's also no atmosphere to retain any heat.

Mercury rotates once every 58.6 days, and revolves around the Sun once every 88 days. For a very long time, we thought Mercury rotated synchronously, meaning that it kept

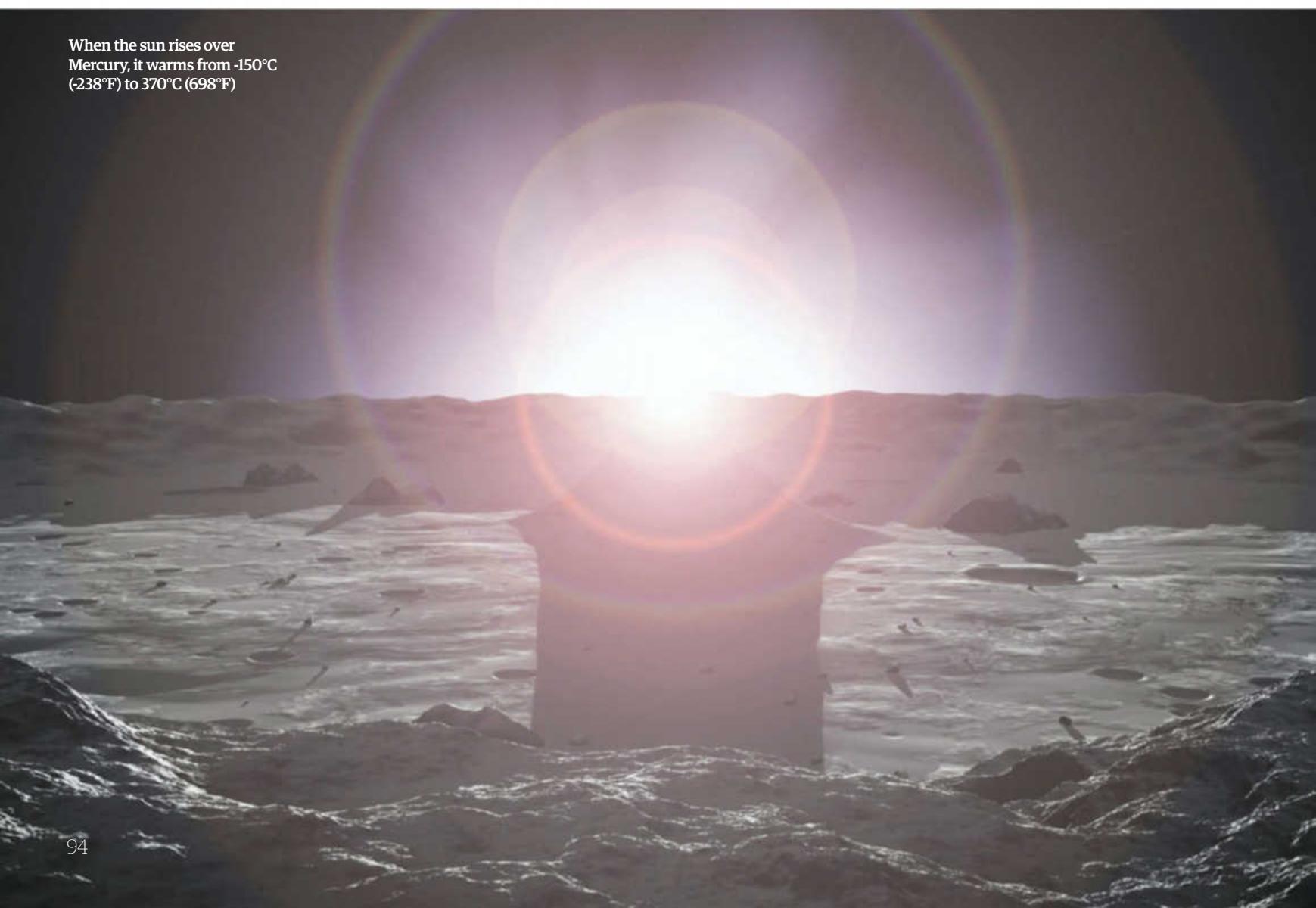
the same side facing the Sun at all times (like the Earth's Moon does), and rotated once for each orbit. Instead, it rotates one and a half times for every trip around the Sun, with a 3:2 spin-orbit resonance (three rotations for every two revolutions). That means its day is twice as long as its year. Even stranger than this, when Mercury is at its perihelion (closest to the Sun), its revolution is faster than its rotation. If you were standing on the planet's surface, the Sun would appear to be moving west in the sky, but then stop and start moving very slowly eastward for a few days. Then as Mercury starts moving away from the Sun in its rotation (known as aphelion), its revolution slows down and the Sun starts moving westward in the sky

again. Exactly how this might appear to you would depend greatly on where you were located on the planet and where the Sun was in the sky overhead. In some places it might look like there were multiple stops, reverses and starts in the rising and setting of the Sun, all in one day. Meanwhile, the stars would be moving across the sky three times faster than the Sun.

Mercury has the most eccentric orbit of any planet, meaning it's nowhere near a perfect circle. Its eccentricity is 0.21 degrees, resulting in a very ovoid orbit. This is part of the reason for its extreme temperature fluctuations as well as the Sun's unusual behaviour in its sky. Not only is it eccentric, it's also chaotic. At times in Mercury's orbit, its eccentricity may

**"Mercury has a diameter of 4,880km (3,032 mi); the Sun's diameter is 1,392,000km (865,000 mi)"**

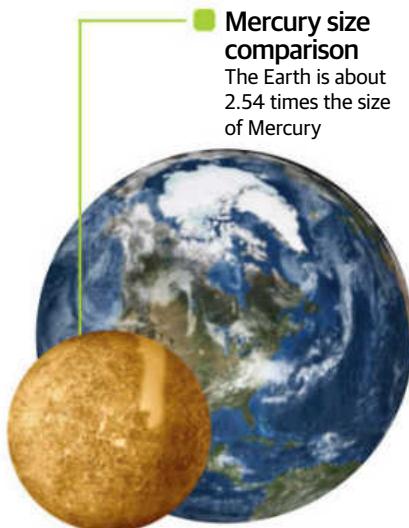
**When the sun rises over Mercury, it warms from -150°C (-238°F) to 370°C (698°F)**



be zero, or it may be 0.45 degrees. This is probably due to perturbations, or interactions with the gravitational pulls of other planets in space. These changes have happened over millions of years, and currently Mercury's orbit - specifically its perihelion - is changing by 1.56 degrees every 100 years. That's much faster than Earth's advance of perihelion, which is 0.00106 degrees every century. Some models show that increases in perturbations could cause Mercury to collide with Venus millions of years from now, but it's a very small chance.

Mercury's chaotic, eccentric orbit is inclined from the Earth's ecliptic plane by seven degrees. Because of this, transits of Mercury - when the planet is between the Earth and the Sun in its rotation - only occur about once every seven years on average. But like so many things about Mercury, its averages don't tell the whole story. For example, there was a transit of Mercury (when it appears to us as a small black dot across the face of the Sun) in 1999, in 2003, and in 2006...

but the next one won't happen until 2016. They usually happen in May (at aphelion) or November (at perihelion), and the latter come more frequently. Transits may also be partial and only seen in certain countries. They're occurring later as the orbit changes. In the early 1500s, they were observed in April and October. ■



## Mercury's orbit

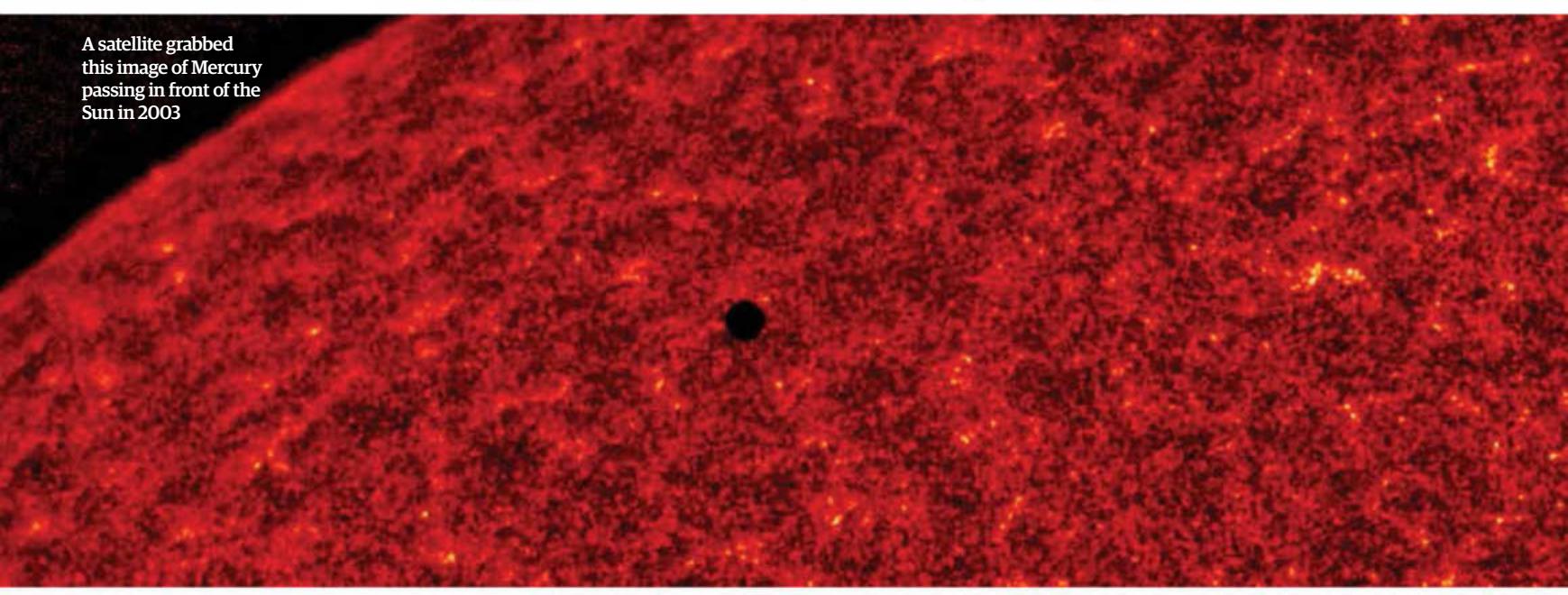
### Perihelion

At this closest point to the Sun, the perihelion, Mercury comes within 46 million km (28.5 million mi)

**Aphelion**  
At its aphelion, the furthest point in its orbit from the Sun, Mercury is 70 million km (43.5 million mi) from the Sun



A satellite grabbed this image of Mercury passing in front of the Sun in 2003



## The planets in relation to the Sun

Mercury lies 57 million km (36 million mi) from the Sun on average, and 77 million km (48 million mi) from Earth

All figures = million miles from Sun

### Mercury

Closest to the Sun and the smallest planet in the Solar System

Mercury 36

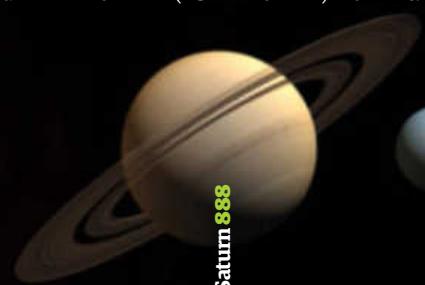
Venus 67

Earth 93

Mars 142



Jupiter 484



Saturn 888

Uranus 1,784



Neptune 2,799

Pluto 3,650

# Mercury inside and out

Mercury has a huge core and a higher concentration of core iron than any other planet

Mercury contains about 30 per cent silicate materials and 70 per cent metals. Although it's so small, this make-up also means that it's incredibly dense at 5,427 grams per cubic centimetre, only a little bit less than the Earth's mean density. The Earth's density is due to gravitational compression, but Mercury has such a weak gravitational field in comparison to the Earth's. That's why scientists have decided that its density must be due to a large, iron-rich core. Mercury has a higher concentration of iron in its core than any other major planet in the Solar System. Some believe that this huge core is due to what was going on with the Sun while Mercury was forming. If Mercury formed

before the energy output from the Sun stabilised, it may have had twice the mass that it does now. Then when the Sun contracted and stabilised, massive temperature fluctuations vaporised some of the planet's crust and mantle rock. Or a thinner mantle and crust may have always existed due to drag on the solar nebula (the Sun's cloud of dust and gas from which the planets formed) from the close proximity to the Sun itself. Our latest information from the Messenger spacecraft supports the latter theory, because it has found high levels of materials like potassium on the surface, which would have been vaporised at the extreme temperatures needed for the former theory.

## The structure of Mercury

### Huge impact

Because the mantle is so thin compared to the core, some believe that there may have been a huge impact of some type that stripped away some of the original mantle

### Bombardment

The current crust may have formed after the bombardment, which was followed by volcanic activity that resulted in lava flows

## Mercury's lack of atmosphere

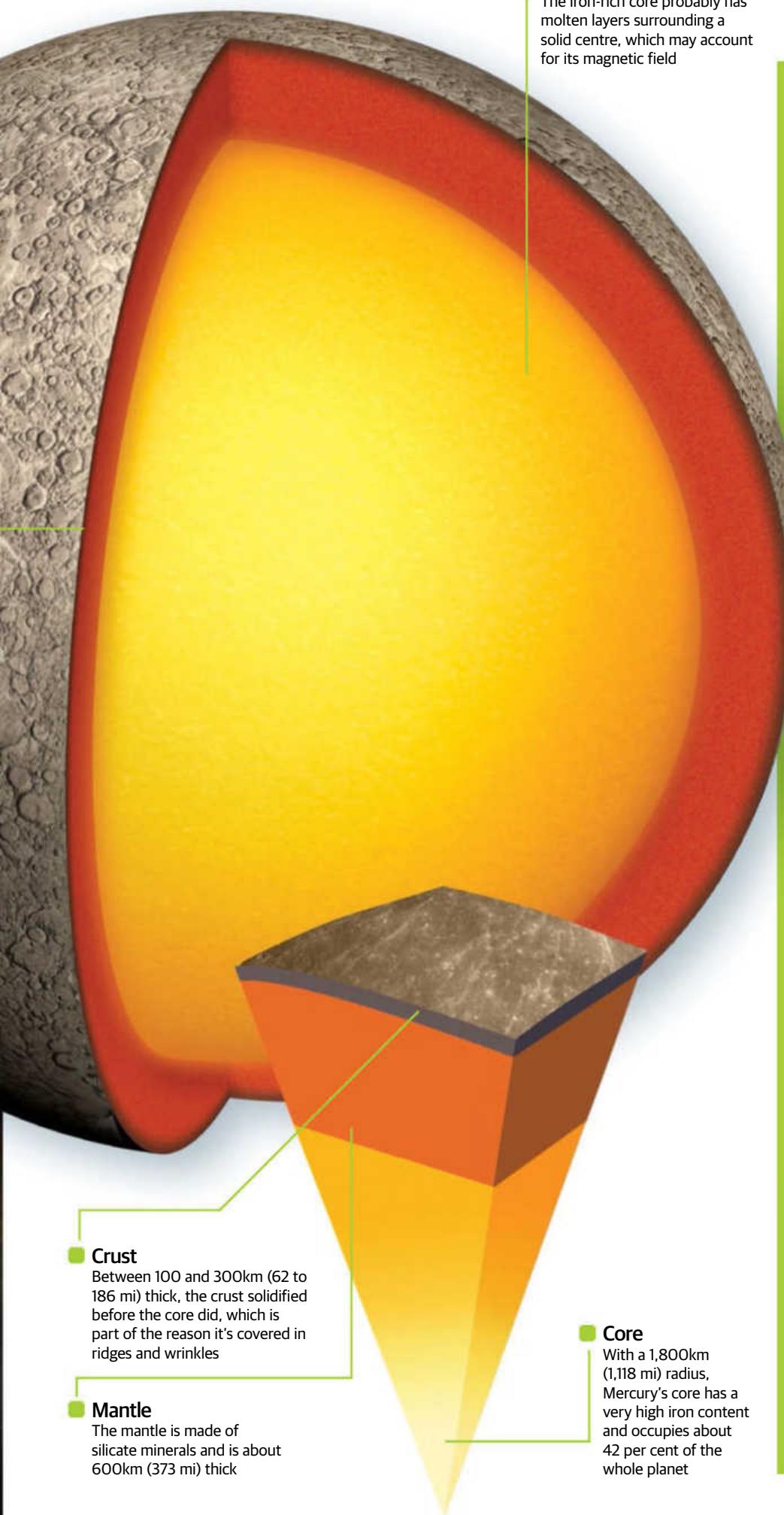
**Solar wind**  
This stream of charged particles ejected by the Sun are deflected by the magnetic field

**Bow shock**  
When the solar wind gets close to the magnetopause, it slows down abruptly

**Magnetopause**  
This is the boundary between the surrounding plasma from solar wind and Mercury's magnetosphere

**Space weathering**  
Mercury's surface is weathered by the impact of both solar plasma and micrometeoroids

**Micrometeoroids**  
These tiny pieces of meteor generally weigh less than a gram

**Molten layers**

The iron-rich core probably has molten layers surrounding a solid centre, which may account for its magnetic field

## Mercury in numbers

Fantastic figures and surprising statistics about Mercury

**176**  
*2nd*  
DAYS

*Mercury revolves in 59 Earth days but it takes 176 days for the Sun to return to the same point in the sky*

**2nd**  
Densest planet in the Solar System after Earth

**427°**  
Mercury's maximum surface temperature

**2.5X** bigger

The Sun appears two and a half times larger in Mercury's sky than it does in Earth's

**45%**

*Until the Messenger spacecraft began imaging Mercury in 2008, we'd only ever seen this much of the planet*

**0**

**moons**  
Mercury is one of the few planets which has no moons or satellites captive within its gravity well

**7x stronger**

The Sun's rays are seven times stronger on Mercury than they are on Earth

**Crust**

Between 100 and 300km (62 to 186 mi) thick, the crust solidified before the core did, which is part of the reason it's covered in ridges and wrinkles

**Mantle**

The mantle is made of silicate minerals and is about 600km (373 mi) thick

**Core**

With a 1,800km (1,118 mi) radius, Mercury's core has a very high iron content and occupies about 42 per cent of the whole planet

# On the surface

Mercury is a planet of extreme variations in temperature, in its surface features and in its magnetic field

The surface of Mercury is not very well understood, but mapping by Mariner 10 and Messenger has revealed numerous craters and plains regions, crisscrossed with compression folds and escarpments. Not long after it formed, the planet was hit heavily and often in at least two waves by large asteroids and comets, which caused its extremely cratered surface. Couple this with periods of strong volcanic activity, which resulted in the smooth plains, and you have a very hilly surface.

Mercury can reach 427 degrees Celsius (800 degrees Fahrenheit), and there's a big difference between the

temperature at the equator and the temperature at its poles. It has the most temperature variations of any planet in the Solar System, getting as low as -183 degrees Celsius (-297 degrees Fahrenheit). There may be deposits of minerals and ice within craters near the poles. The deepest craters are located there, and are the most likely candidates to hold ice because they always stay shadowed, never rising above -173 degrees Celsius (-279 degrees Fahrenheit).

Because of its small size and wide changes in temperature, Mercury doesn't have a true atmosphere. It has an unstable exosphere, a very

loose, light layer of gases and other materials. Gases within it include helium, oxygen and hydrogen, some of which come from solar wind. Minerals such as calcium and potassium enter the exosphere when tiny meteors strike the surface and break up bits of rock. Mercury also has a magnetosphere, formed when the solar wind interacts with its magnetic field. Although that magnetic field is only about one per cent as strong as Earth's, it traps in some plasma from the solar wind, which adds to its surface weathering. The Messenger spacecraft discovered that Mercury's magnetosphere is

somewhat unstable, causing bundles of magnetic fields to be pulled out into space and wrapped into tornado-like structures by the passing solar wind. Some of these tornadoes are as long as 800 kilometres (497 miles), or about a third of the planet's size. Before Mariner 10 flew by Mercury, it was thought not to have a magnetic field at all. The current theory is that it is caused by a dynamo, much like Earth's magnetic field, which means that the planet has an outer core of electrically conductive, rotating molten iron. Not all scientists agree that Mercury is capable of generating a dynamo, however.

## Pit-floor craters

These craters are irregularly shaped and may be formed by the collapse of magma chambers below the surface

## Impact craters

These craters can be hundreds of kilometres across, and can be fresh or very decayed

## Plains

There are both smooth and rolling or hilly plains, which may be the result of either volcanic activity or impacts

## Scars

These steep cliffs can occur due to either erosion or compression within the planet's interior



**"Because of its small size and wide changes in temperature, the planet doesn't have a true atmosphere"**

# Mercury mapped by Mariner

## Caloris Basin

Not only is Caloris the largest impact crater on the planet, at 1,550 km (960 mi) in diameter, it's one of the largest ones in the Solar System

## Sobkou Planitia

This plains region is home to several craters. Sobkou is the Egyptian messenger god

## Budh Planitia

The plains were named using alternative names for Mercury. Budh is its Hindu name

## Tolstoj Basin

The impact that caused this crater is thought to have occurred early in Mercury's history

## Bello

Bello is a crater named after a South American writer, and is about 129km (80 mi) in diameter

## Borealis Planitia

This basin has a smooth floor and may be similar to the basaltic basins on the Earth's Moon, also called lunar mares

## Blank area

Mariner 10 was only able to map about 45 per cent of Mercury's surface (the night-time side) and missed a few areas on that side as well

## Vivaldi

This prominent crater is about 210km (130.5 mi) wide and features a double ring

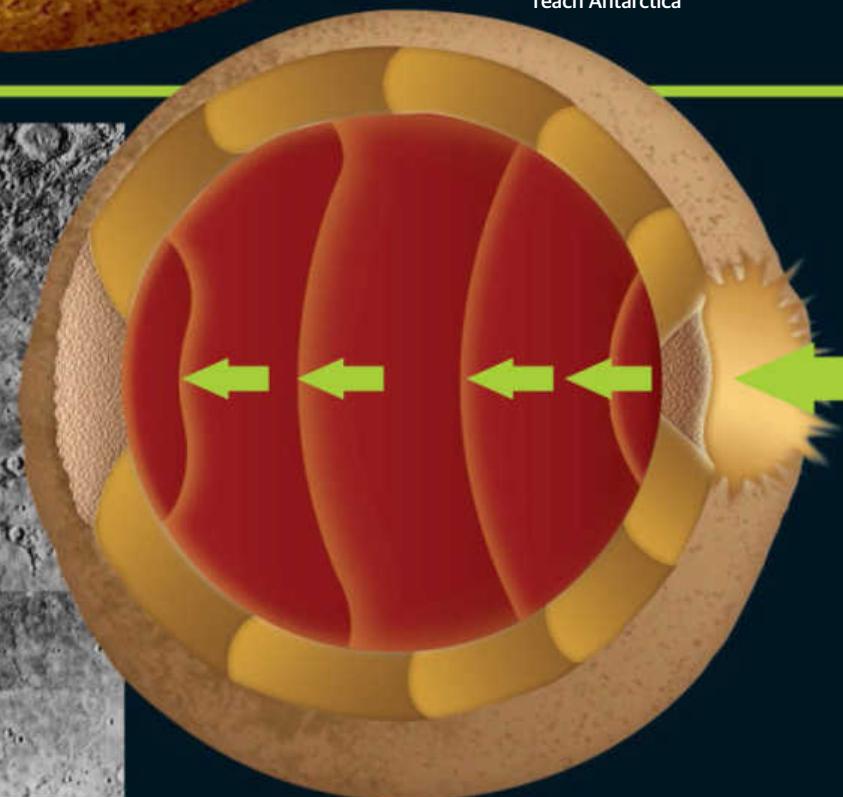
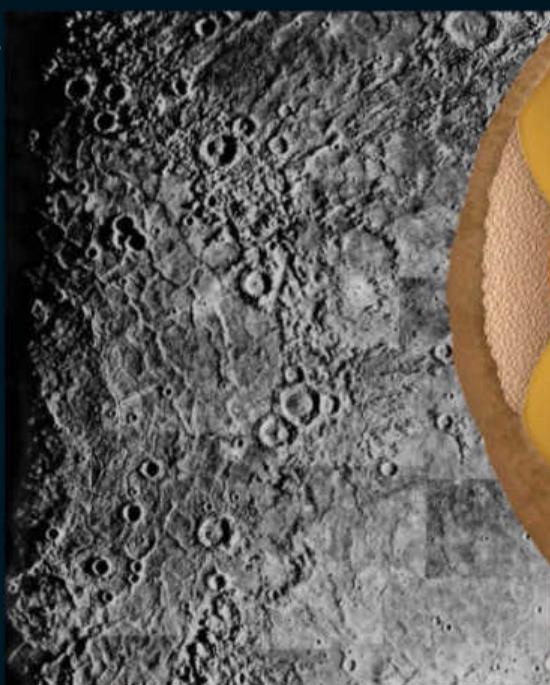
## Fram Rupes

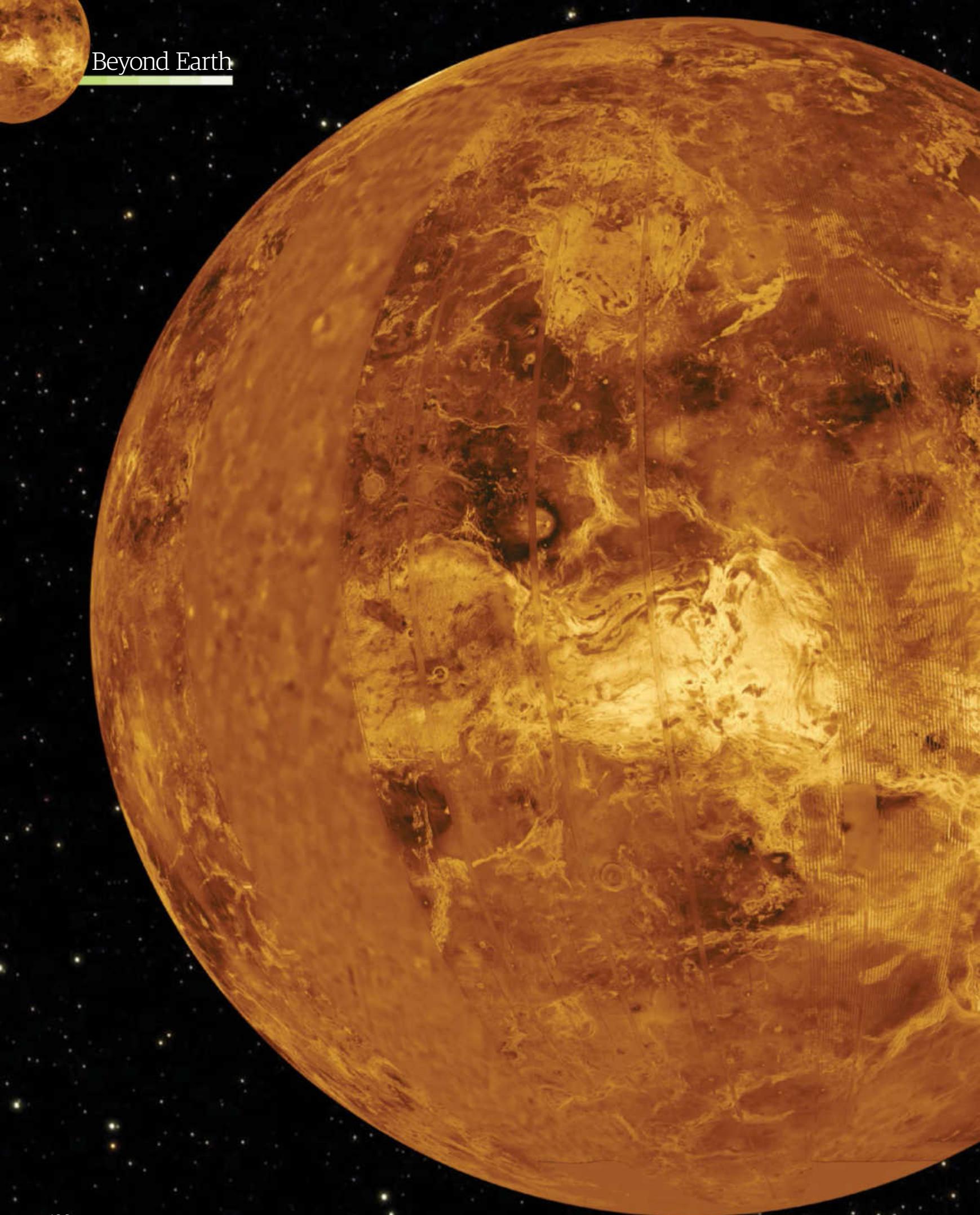
This long cliff was likely formed when Mercury's core cooled and contracted. It is named after the first ship to reach Antarctica

## The Caloris Basin

This diagram shows how the large impact craters on Mercury's surface - and particularly the Caloris Basin - have impacted the rest of the planet. At the antipode (a point on the other side of the planet exactly opposite of the basin), the ground is very uneven, grooved and hilly. It's called the Chaotic Terrain because it stands out so much among the otherwise smooth plains. The terrain may have formed due to seismic waves or material actually ejected from the antipode.

The image of Mercury's surface was taken at a distance of about 18,000km (11,100 mi)





# All About... VENUS

Venus is the most Earth-like planet in the Solar System, but there are a few key differences between the two planets, such as clouds of acid and temperatures hot enough to melt lead. Read on to discover more about Earth's 'evil twin'

Venus, named after the Roman goddess of love and beauty, is a study in contradictions. It was likely first observed by the Mayans around 650 AD, helping them to create a very accurate calendar. It's well-known to us because of its apparent magnitude, or brightness, in our sky - the second-brightest after our own Moon. It's most visible at sunrise and sunset, and like Mercury was thought of as two different planets by the Ancient Egyptians - Morning Star and Evening Star. It's the second-closest planet to the Sun, the closest planet to Earth, and the sixth-biggest planet in the Solar System.

Venus is often described as the Earth's 'twin' or 'sister planet'. Like Earth, Venus is a rocky planet, with a mass that's 81.5 per cent of the Earth's mass. It's 12,092 kilometres (7,514 miles) in diameter, which is just 650 kilometres (404 miles) shy of Earth's diameter. Both planets have relatively young surfaces, with few craters. But that's where the similarities end. Venus has been called possibly one of the most inhospitable planets in the Solar System, because lurking beneath its dense cloud cover is an atmosphere that's anything but Earth-like, which is why some astronomers have taken to calling it Earth's 'evil twin' instead.

Of all the planets, Venus has the most circular orbit, with an eccentricity (deviation from a perfect circle) of 0.68 per cent. By comparison, the Earth has an eccentricity of 1.67 per cent. Venus comes within 108 million kilometres (67 million miles) of the Sun on average. When it happens to lie between the Sun and the Earth - which occurs every 584 days - it comes closer to the Earth than any other planet. Around 38 million kilometres (24 million miles) close, that is. Because Venus's orbit around the Sun passes inside the Earth's orbit, it also goes through phases that go from new to full and back to new again. These phases are the different

variations of light emanating from it as seen from the Earth, much like the Moon's phases. When Venus is new (not visible) it is directly between the Earth and the Sun. At full, it is on the opposite side of the Earth from the Sun. These phases were first recorded by Galileo in 1610.

The rarest of predictable events in our Solar System involve Venus. Known as transits of Venus, this only happens once every 243 years in a pattern. A transit is somewhat like a solar eclipse, occurring when the planet is between the Earth and the Sun. Transits of Venus happen eight years apart, then with gaps of 105.5 years and 121.5 years between them. The odd pattern has to do with the relationship between the orbital periods of the two planets. Usually they happen in pairs, but not always. During a transit, Venus looks like a tiny black disc passing across the Sun's surface. The first modern observation of a transit of Venus occurred in 1639, while the most recent was on 5 and

"Venus rotates clockwise, making a Venusian sidereal day last the equivalent of 243 days on Earth"

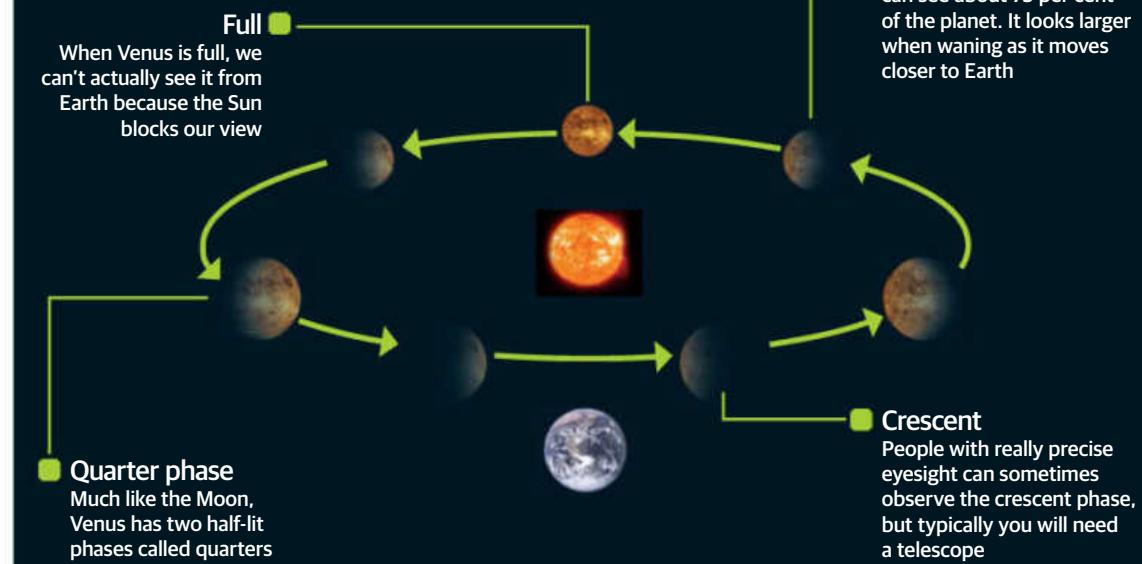
6 June 2012. The transits have always provided astronomers with lots of information about not only Venus, but our Solar System. The earliest helped gauge the size of the Solar System itself, while the one in 2012 is hoped to help us find planets outside our Solar System, or exoplanets.

What else sets Venus apart? Its retrograde rotation. Every planet orbits the Sun anti-clockwise, and most of them rotate anti-clockwise, too. But Venus rotates clockwise, making a Venusian sidereal day last about 243 Earth days - incidentally one of the slowest rotations of any planet. But its orbit around the Sun lasts 224.7 days, making Venus's days longer than its years. All of this means that if

you were standing on the surface of the planet, you'd see the Sun rise in the west and set in the east, but only every 116.75 Earth days or so.

Many astronomers have wondered why Venus has such a circular orbit and unusual rotation. All planets came from the solar nebula - matter left over from the formation of the Sun - but maybe Venus had a more violent beginning. One theory is that it formed from the collision of two smaller planets, which impacted at such high speeds that they simply fused together, leaving very little debris. Another is that the planet experienced other multiple impact events - and even had one or more moons - that caused its spin to reverse. ■

## Venus's orbit

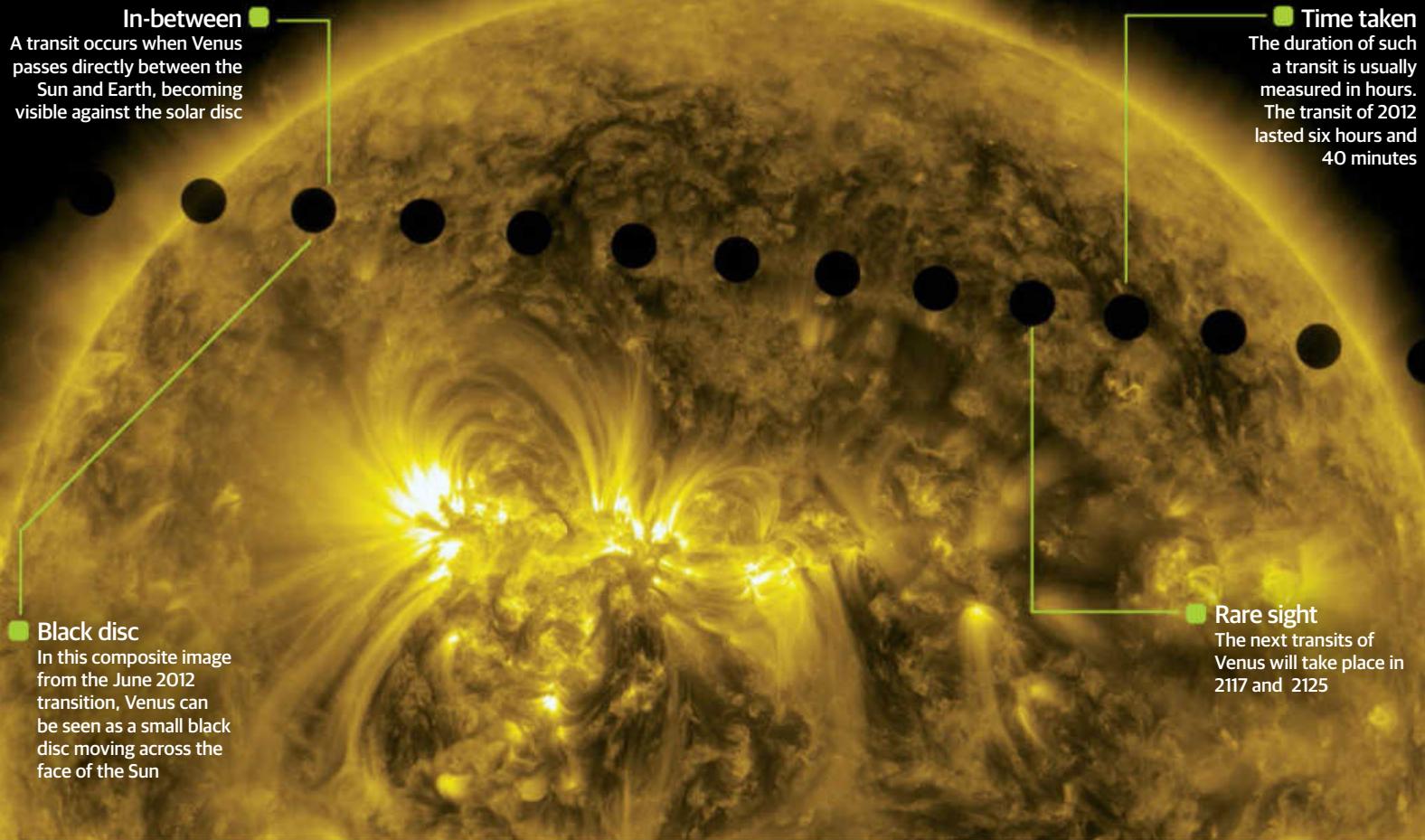


## The planets in relation to the Sun

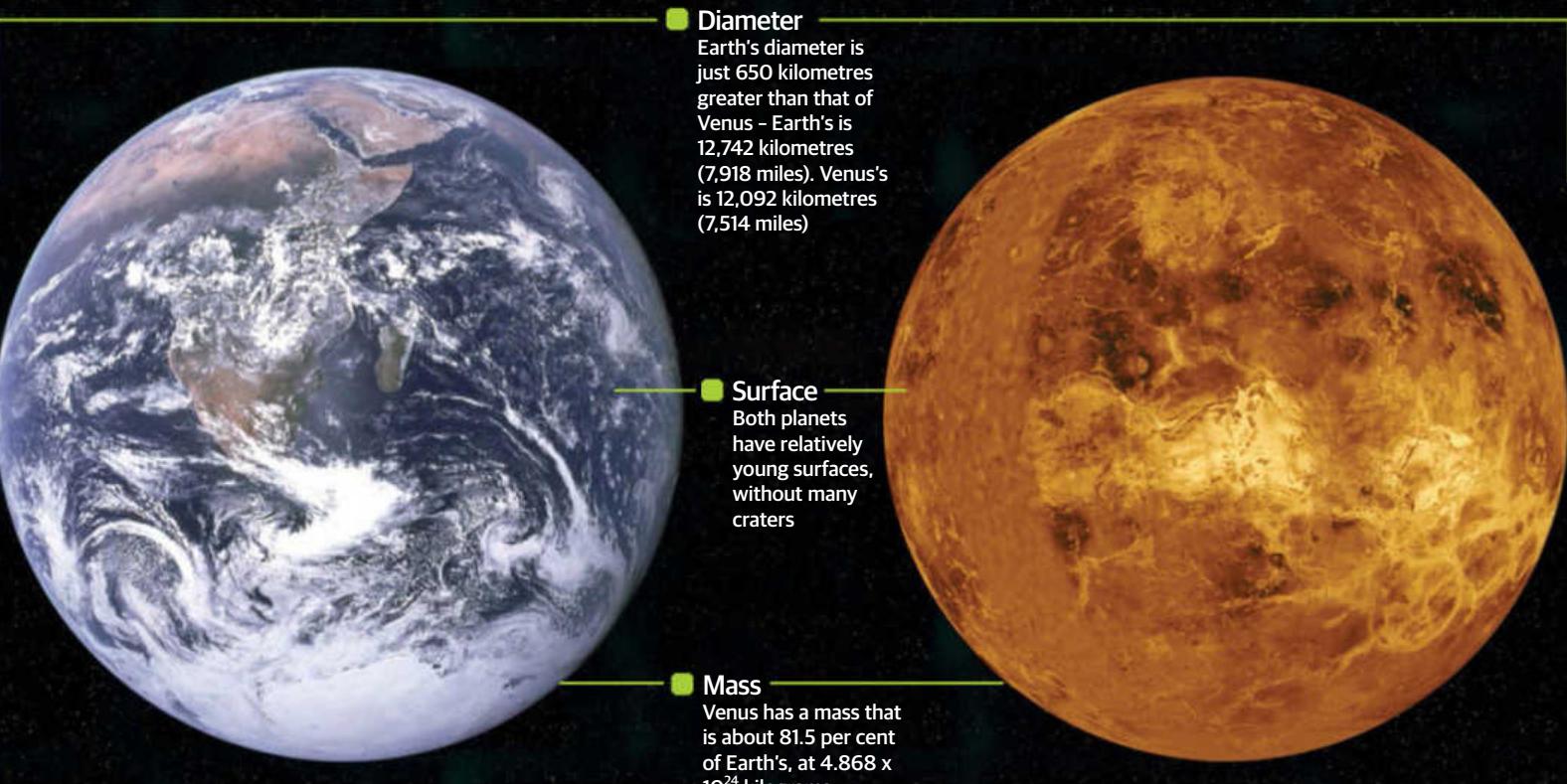
Venus lies 108 million km (67 million mi) from the Sun and 38 million km (24 million mi) from Earth



# The transit of Venus



## Earth's twin planet



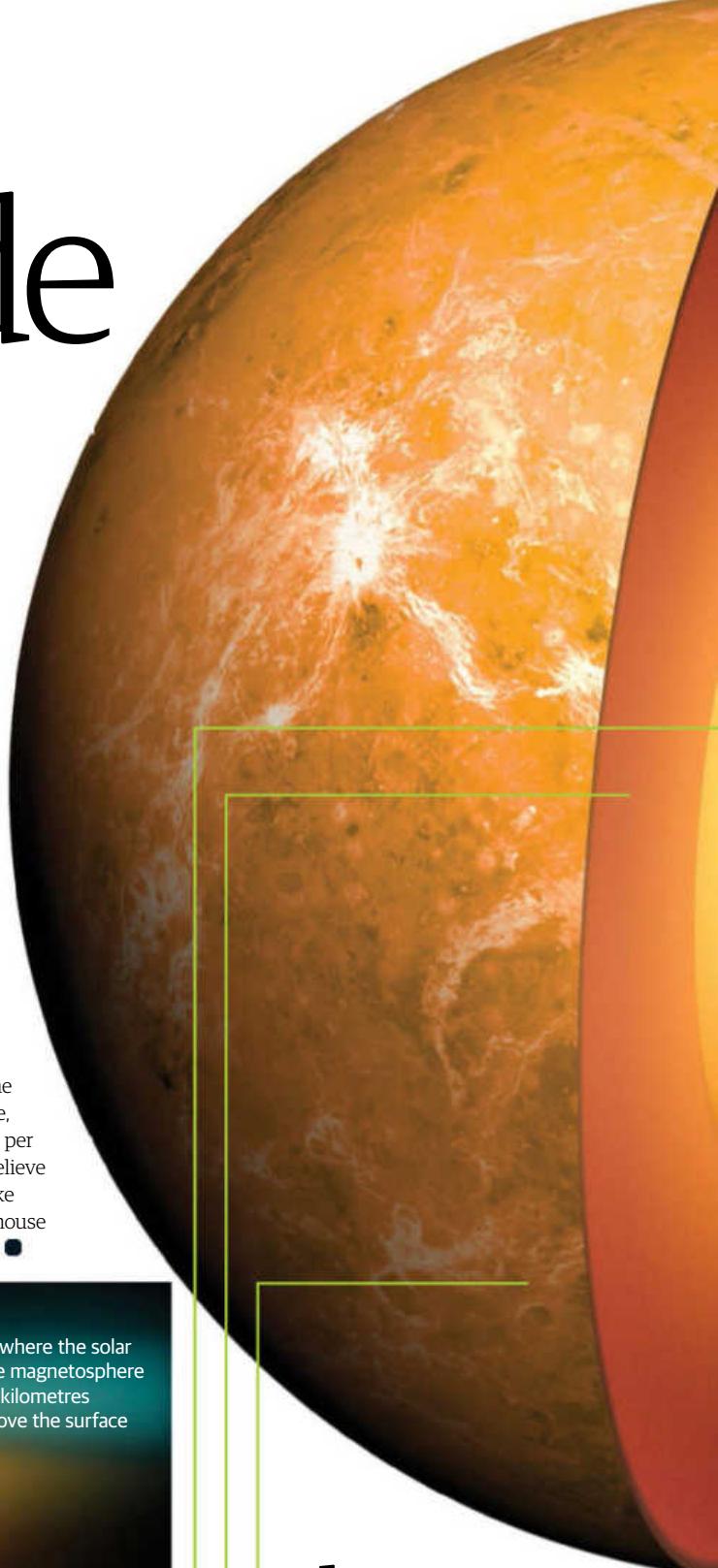
# Venus inside and out

We don't know much of Venus's interior, and what we know of its atmosphere isn't pretty

While our knowledge of Venus's internal make-up is mostly based on speculation, we do know that it does not include a dynamo, like Earth's. A dynamo is a convecting, rotating fluid that conducts electricity and is responsible for a planet's magnetic field. Venus may have a liquid outer core and that conducts electricity, but does not convect and rotates too slowly to produce a dynamo. The Earth has a dynamo in part because its liquid core is hotter on the bottom than on the top, creating convection. Venus's core may be all one temperature. But why? Some astronomers believe that Venus was subject to an unknown event on its surface, which caused an end to plate tectonics on the surface and led to a cooling of the core. Venus's core could be completely solid, or it may be completely liquid. What we do know is that its magnetic field, which is incredibly weak, is caused by interactions between the ionosphere (ionised upper atmosphere) and the solar wind.

Venus has the densest atmosphere in the Solar System, with a mass about 90 times that of Earth's

atmosphere. There's a heavy, sulphuric layer of clouds that scatter about 90 per cent of the sunlight that reaches them, which prevents viewing of the planet's surface and keeps it dim. Below the cloud layer is a layer of carbon dioxide, mixed with a bit of nitrogen. Pressure on the surface is 92 times that of Earth's surface. Although Venus is further away from the Sun than Mercury, its atmosphere creates a greenhouse effect that results in an incredibly hot temperature of 460 degrees Celsius (860 degrees Fahrenheit), while Mercury's maximum temperature is just over 420 degrees Celsius (788 degrees Fahrenheit). The temperature stays the same most of the time, and there are winds of up to 300 kilometres per hour (186 miles per hour). Some scientists believe that Venus once had an atmosphere more like Earth's, and even had oceans, but the greenhouse effect eventually evaporated all of the water. ■



## The atmosphere on Venus

### Solar wind

Without a strong magnetic field of its own, Venus's atmosphere is hit with this electrically charged stream of particles from the Sun

### Magnetosphere

Venus's magnetosphere is solely induced by the solar field's interaction with Venus's atmosphere

### Bow shock

This boundary where the solar wind meets the magnetosphere is about 1,900 kilometres (1,181 miles) above the surface

### Magnetotail

The solar wind's pressure on the magnetosphere creates a tail-like structure of plasma flowing away from the planet

## The structure of Venus

### Crust

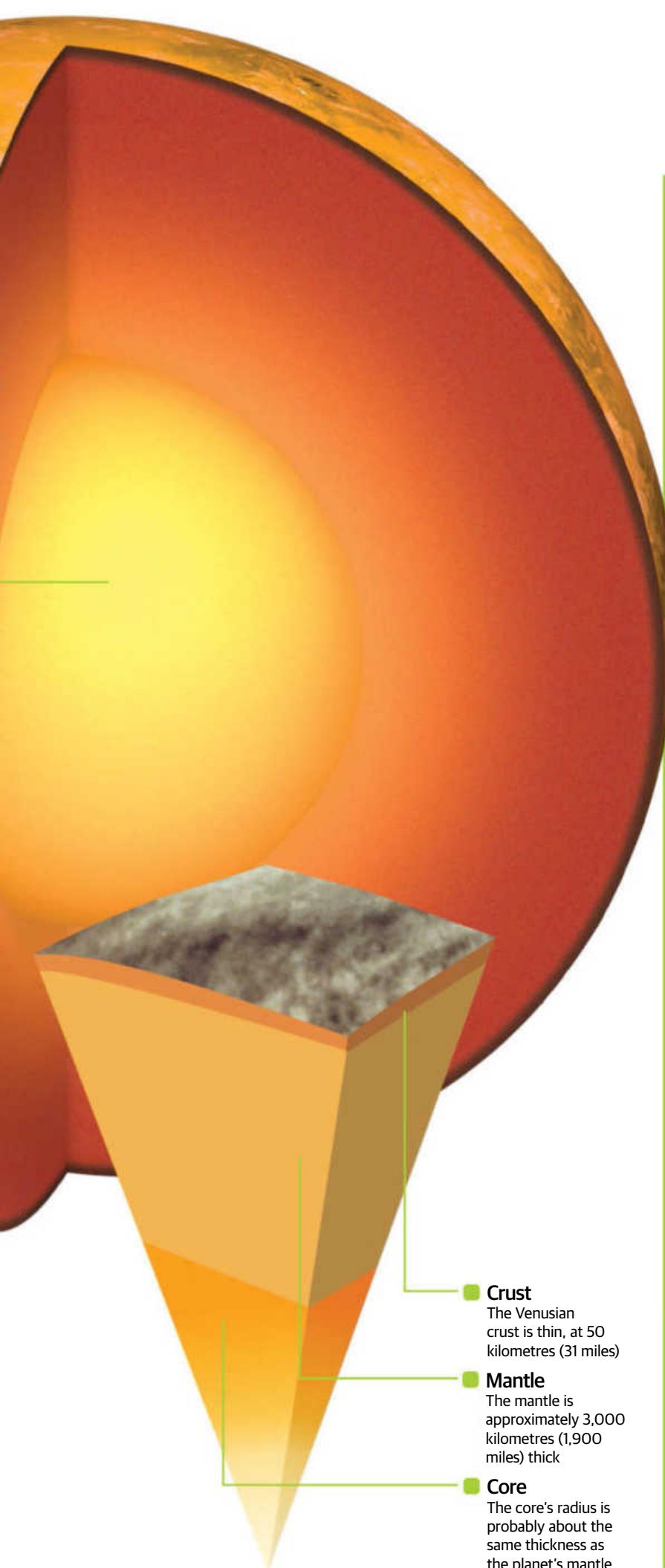
Venus's crust is mainly made up of silicate rocks

### Mantle

The mantle is likely rocky and similar in composition to Earth's

### Core

The core is probably molten metal, but how much of it is liquid and how much is solid remains a mystery

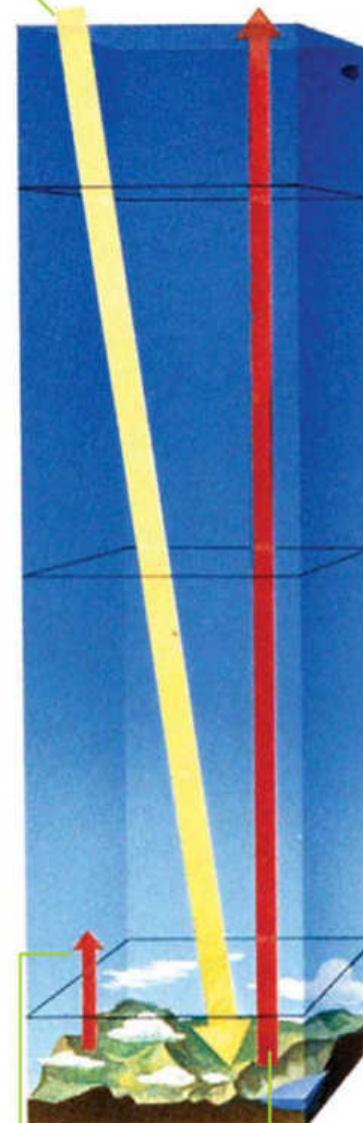


## The greenhouse effect on Venus

How Venus's extreme and inhospitable temperatures are created

### Incoming sunlight

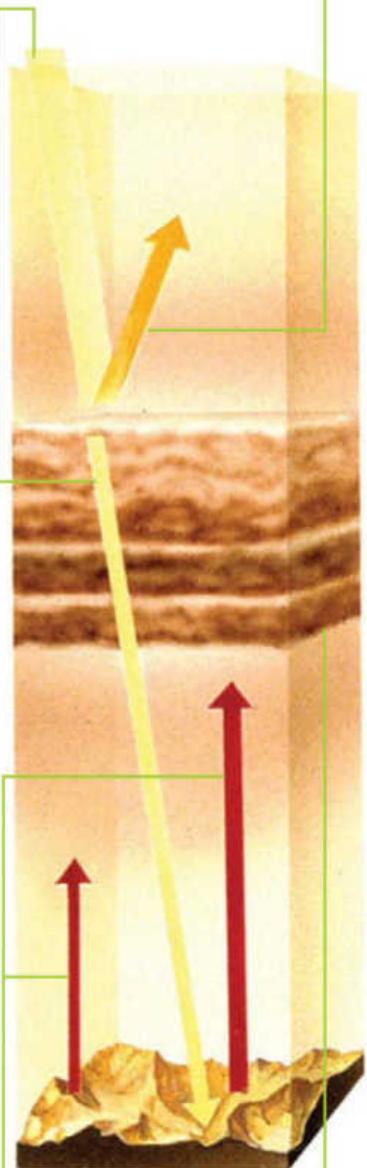
Most of the sunlight passing through Earth's atmosphere makes it through. However, very little sunlight gets through Venus's thick atmosphere



Earth

### Reflected sunlight

Most of the sunlight that reaches Venus is reflected away from the planet before reaching the surface



Venus

### Infrared radiation

Both Venus and Earth emit infrared radiation but most of Venus's does not make it off the planet

**Reflective clouds**  
The heavy cloud cover on Venus means that the planet stays incredibly hot, as most of its heat cannot escape from the planet's atmosphere

# On the surface

Venus is smooth, with a young surface – but it is also covered in volcanoes and lava flows that may have lasted for millions of years

Everything that we've learned about Venus's surface is from radar, because the atmospheric pressure is too great for a probe to survive longer than an hour. But Magellan has mapped most of the surface, and showed that Venus has a lot of interesting surface features. It has a relatively flat surface, with about 13 kilometres (eight miles) between the lowest point and the highest point. Most of them fall into one of three categories: highlands, deposition plains and lowlands. There are also some mountain ranges, with the highest one, Maxwell Montes at 11 kilometres (6.8 miles). The highlands comprise about ten per cent of the planet's overall surface area, and there are two main 'continents' – Ishtar Terra and Aphrodite Terra. The deposition plains (formed from lava

flows) cover over half of the surface, and the rest of the planet is lowlands.

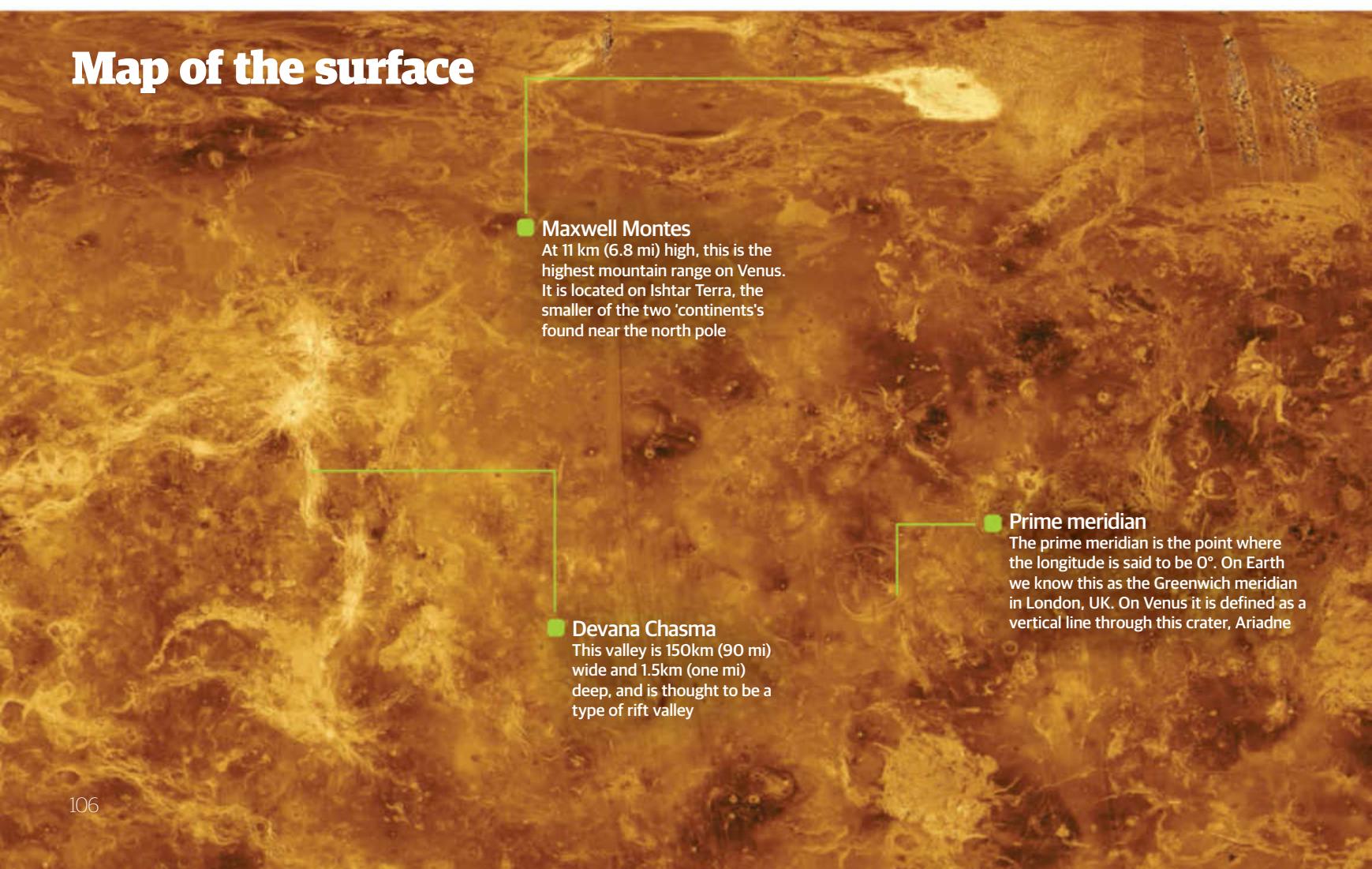
Venus has a relatively smooth surface compared to the other terrestrial planets, but this is probably because the atmosphere burns up smaller meteors before they can reach the surface. There are still about 900 impact craters, and few of them are smaller than 30 kilometres (19 miles). The lower number of craters and their apparent youth shows that Venus's surface is young. Of course the planet itself isn't young, so this points to major events that have remapped the surface entirely. Scientists theorise that these events happened about 300 million years ago, and probably were due to low-viscosity lava flows that lasted for millions of years. One theory is that decaying radioactive elements

heated up in the mantle, eventually forcing their way to the surface. The lava flows covered most of the planet, and then the mantle cooled down periodically. Venus doesn't have tectonic plates like Earth, but has a lot of features typically associated with plate tectonics.

The most prominent features on Venus are due to volcanism. These include about 150 large shield volcanoes, many of which are called pancake domes because they're very wide and flat. They are usually less than one kilometre (0.6 miles) tall and up to 65 kilometres (40 miles) in diameter, and they're often found in clusters called shield fields. The shape is probably due to both the high pressure atmosphere and thick, silica-rich lava. There are also what may

be hundreds of thousands of smaller volcanoes. Venus also has some other volcanic features, including one that has only been seen in one other place in the Solar System – Uranus's moon Miranda. Coronae are ring-shaped structures usually about 300 kilometres (180 miles) across and hundreds of metres above the surface. They probably form when magma pushed up parts of the crust into a dome, but cooled and leaked out as lava. The centre collapsed, resulting in a ring. Venus also has arachnoids, networks of radiating fractures in the crust that resemble a spider's web. They may form the same way as novas, ridges and trenches that come from magma pushing through the surface, but astronomers don't know for sure. ●

## Map of the surface

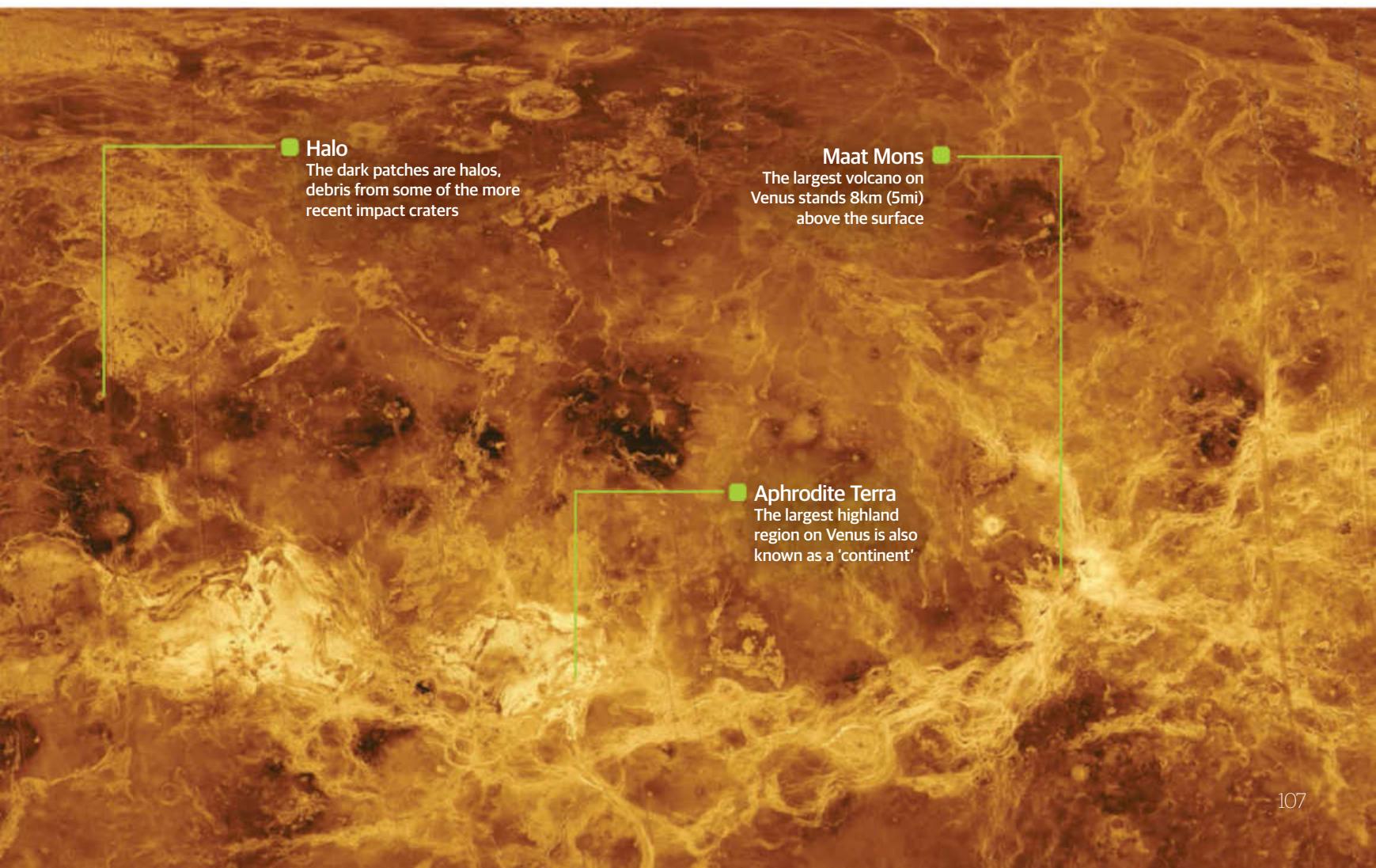
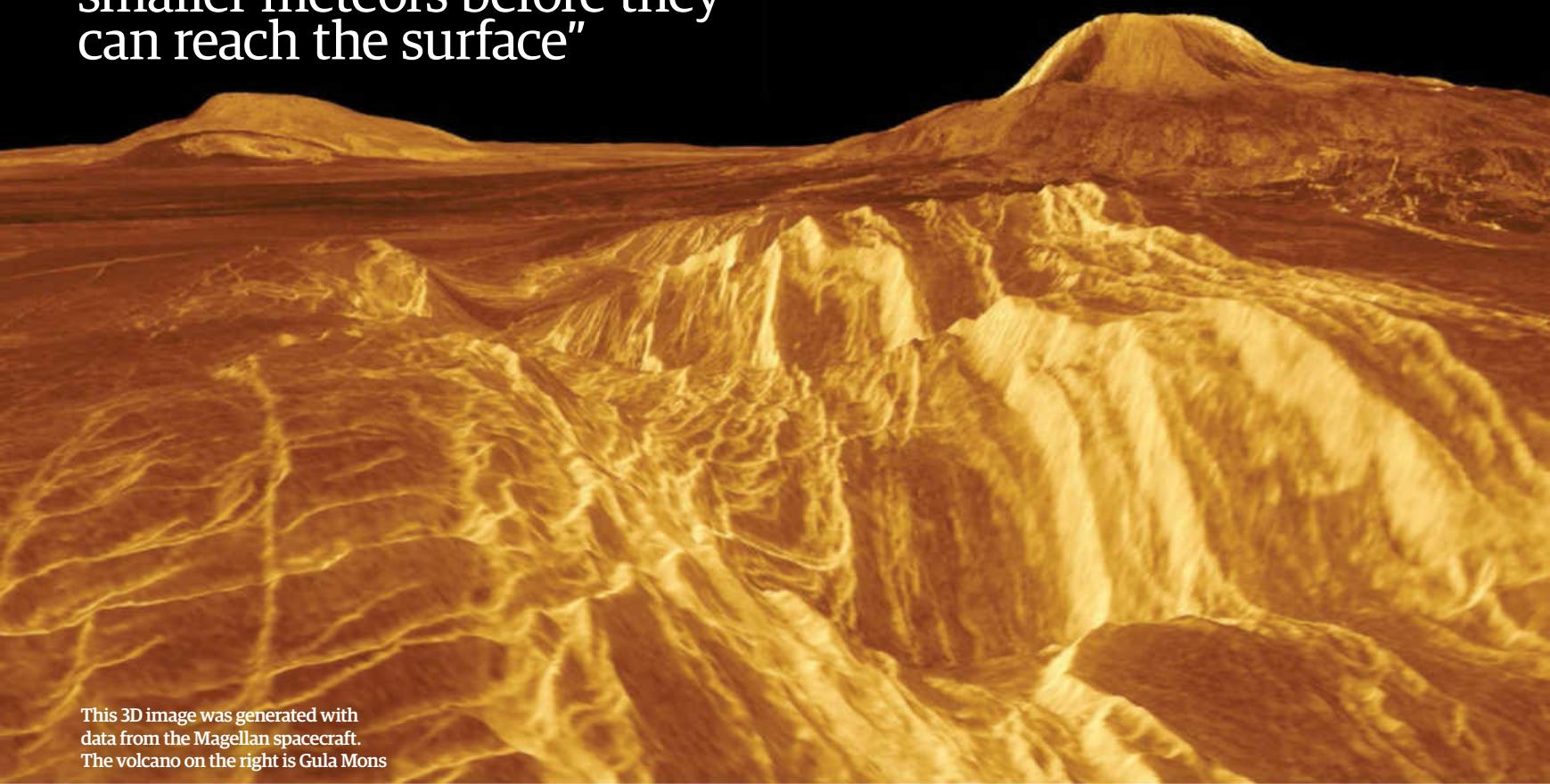


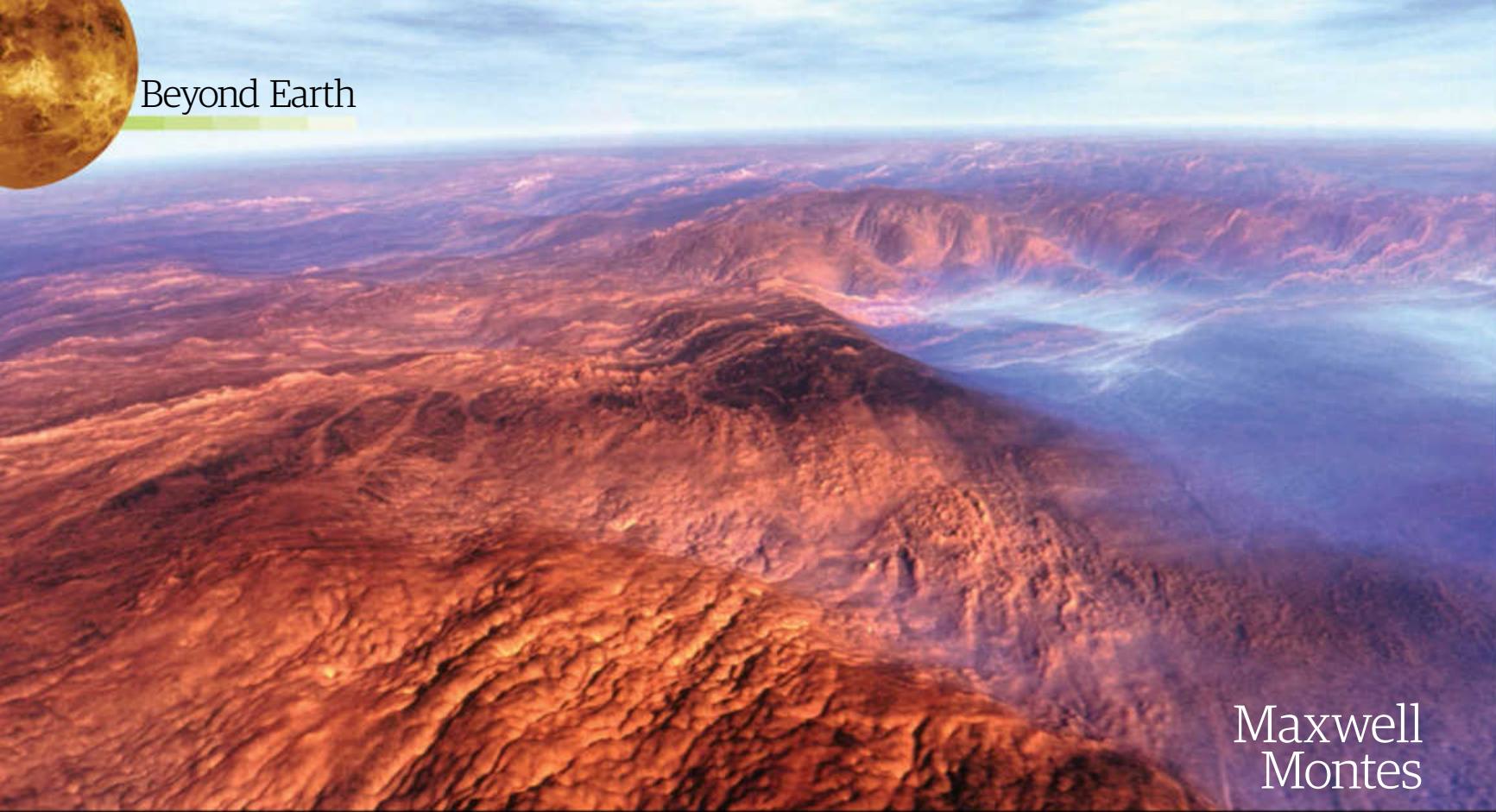
**Maxwell Montes**  
At 11 km (6.8 mi) high, this is the highest mountain range on Venus. It is located on Ishtar Terra, the smaller of the two 'continents' found near the north pole

**Devana Chasma**  
This valley is 150km (90 mi) wide and 1.5km (one mi) deep, and is thought to be a type of rift valley

**Prime meridian**  
The prime meridian is the point where the longitude is said to be 0°. On Earth we know this as the Greenwich meridian in London, UK. On Venus it is defined as a vertical line through this crater, Ariadne

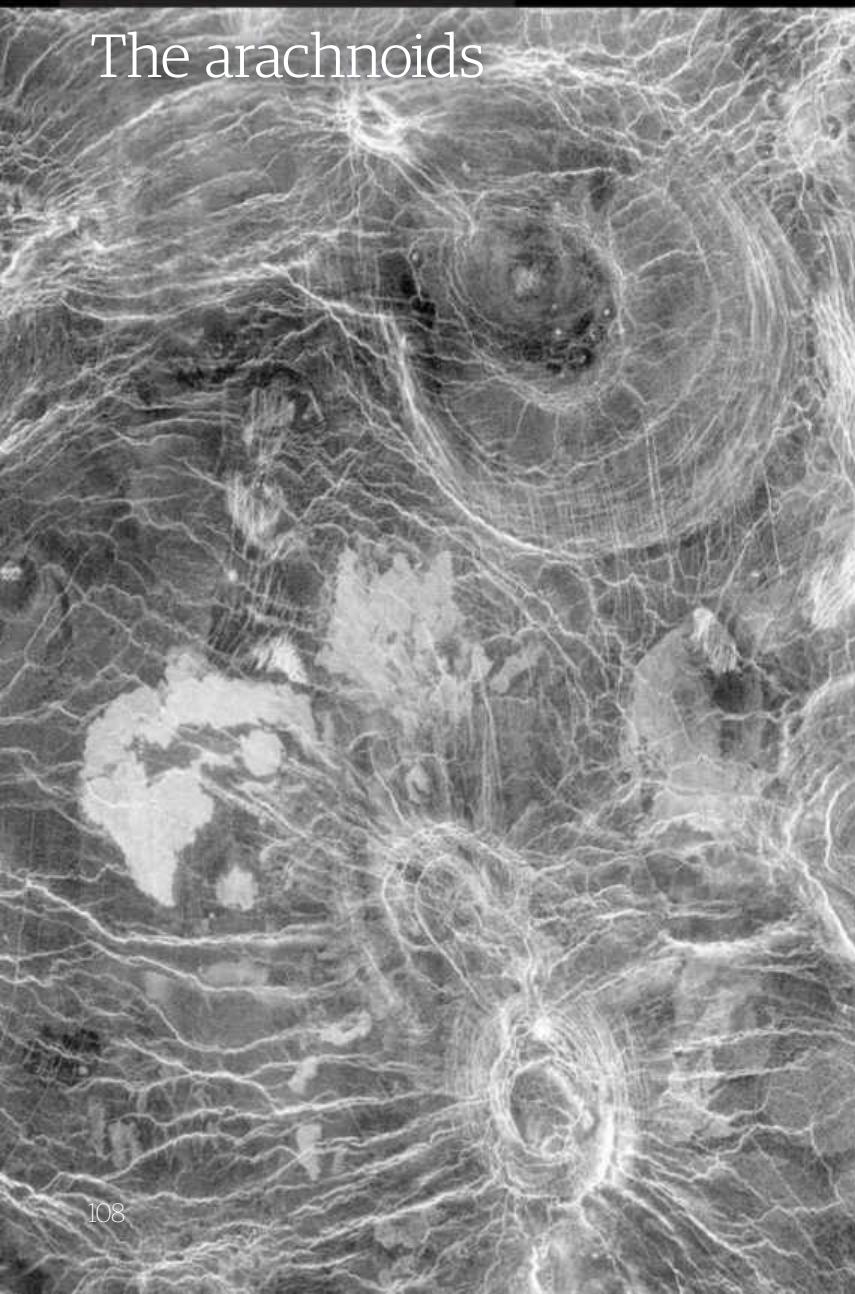
"Venus is smooth because the atmosphere burns up smaller meteors before they can reach the surface"





Maxwell  
Montes

The arachnoids



# Mountains, volcanoes and craters

The extraordinary features that dominate the surface of Venus

## Maxwell Montes

Maxwell Montes is the tallest mountain range on Venus, reaching 11 kilometres (6.8 miles) above the mean planetary radius. By comparison, the tallest mountain on Earth, Mount Everest, is 8.8 kilometres (5.5 miles) tall. Although this is a computer-generated image, it was formed using data from the Magellan spacecraft.

## The arachnoids

Spider-web like formations crawl across the surface of Venus. Arachnoids are formations of unknown origin that look like concentric circles of cracked crust. They can cover as much as 200 kilometres (124 miles).

## Mead Crater

A crater almost as big as the largest crater on Earth. Mead Crater, named after anthropologist Margaret Mead, is the largest impact crater on Venus's surface. It's 280 kilometres (170 miles) wide, just 20 kilometres shy of Earth's

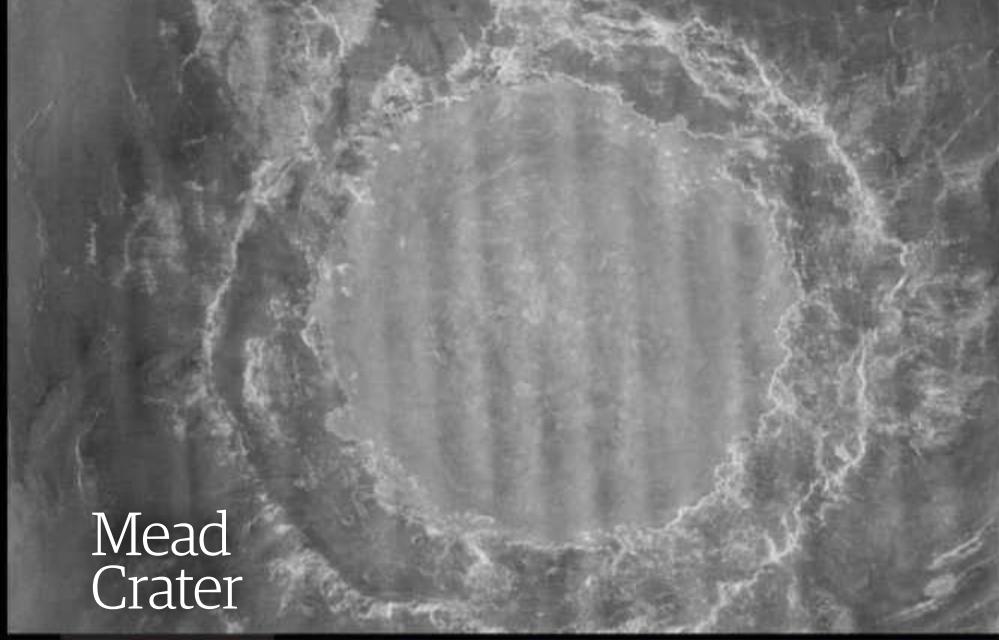
widest crater Vredfort. It has an inner and outer ring and is located north of Aphrodite Terra.

## Maat Mons

Maat Mons is eight kilometres (five miles) above the surface of Venus, and is its highest volcano. It has a huge caldera, or cauldron-shaped collapse, about 28 kilometres (17 miles) by 31 kilometres (19 miles). The caldera contains five smaller craters as a result of the volcano's collapse. Magellan revealed relatively recent volcanic activity in the area.

## Pancake domes

Venus is known for unique volcanic formations called pancake domes. These pancake dome volcanoes are located in the Eistla region of Venus. They're about 65 kilometres (40 miles) in diameter with tops that are less than one kilometre (0.6 mile) in height. These volcanoes are formed when viscous lava is extruded under Venus's high-pressure atmosphere.



Mead  
Crater



Maat Mons



Pancake  
domes

## Venus in numbers

Fantastic figures and surprising statistics about Venus

**243 DAYS**

*It takes 243 days for Venus to rotate but only 225 days for it to orbit the Sun*

**38 million km**

The closest Venus gets to Earth, making it our nearest planetary neighbour

**92x greater**

The pressure on the surface of Venus is 92 times that on Earth

**62%**

*Percentage of the 42 missions to Venus that have been successful*

**450°C**

The maximum temperature on Venus

**1,000**

There are more than 1,000 volcanoes or volcanic craters on Venus

**650km**

Venus is just 650km less than Earth in diameter

# SURVIVING ON MARS

Barren, cold and uninhabitable - will mankind be able to make a home out of the Red Planet?

Stranded on Mars. That's the fate that befalls one unfortunate astronaut in the novel and film *The Martian*. With no way to contact home, he must rely on his skills and the equipment available to stay alive in the face of deadly Martian elements.

While the film and book are both works of fiction, it is true that going to Mars will be the most dangerous crewed space mission ever attempted. There are dust storms, radiation, an unbreathable atmosphere, fierce coldness and low gravity to contend with, while the astronauts themselves will have to constantly be in top physical and mental condition in the most challenging of environments. Should anything go wrong, it is an 18-month wait for

a new launch back home, and then a further eight months travel time. The first astronauts to step foot on Mars will have to look after themselves.

The motto for a future Mars mission might read 'be prepared'. Knowing that astronauts will be on Mars by themselves for a long time, any mission will require all the equipment they could conceivably need to survive, plus back-ups and spares for when things inevitably break. Carrying all this cargo at once would need a big ship, requiring a large amount of fuel. Instead, the idea is to send as much as possible to Mars ahead of the astronauts in the form of pre-cursor missions, so that supplies and a power source is waiting for them when they arrive



# Our path to Mars

Steadily, and with the right technology, we're hoping to land man on the Red Planet

## Relying on Earth

Mission length: 6-12 months

Time to return to Earth: hours

### Humans in orbit

Rockets have allowed astronauts to gain access to space via low-Earth orbit



### International Space Station

We've managed to master the very basics of getting to Mars on the International Space Station

One of these pre-cursor flights will also act as the astronauts' return vehicle to bring them back to Earth. It will make its own rocket fuel by reacting a small amount of hydrogen that it carries with it to Mars with the plentiful carbon dioxide in the Red Planet's atmosphere. This chemical reaction produces oxygen that can be used as rocket propellant. So, if anything does go wrong when the astronauts first touch down on Mars, there will be a ship there ready and waiting guaranteed to be able to bring them home. Their landing craft will also double up as a habitation module, or at least part of one - a place for them to live and work. When the crew is ready to return to Earth, the habitation module is left behind for the next mission to use. An additional habitation module is left behind with each mission, gradually forming the beginnings of a permanent base on Mars.

An advocate of this mission plan is Kevin Nolan, author of the book, *Mars: A Cosmic Stepping Stone*. He highlights that giving Martian astronauts a decent chance of succeeding and surviving in their mission is going to take patience - rushing to Mars would make the astronauts unlikely to come home again.

"If we're to set people on the surface of Mars then it most likely cannot happen before 2040," Nolan says. "The notion of placing people on the surface for a required 500-day stay there requires significant resources such as supply missions two years in advance, landing miniature nuclear power stations on the surface, and providing a facility to manufacture the fuel to be able to return home. All of these are decades away - so this time period is the most likely for actual human missions to the surface."

The dangers of living on Mars relate to the Red Planet's environment. The atmosphere is 95 per cent carbon dioxide with the remaining five percent being made up of nitrogen and argon, and a measly 0.1 per cent of the atmosphere being oxygen. Contrast that

with Earth's friendly atmosphere, which contains 21 per cent oxygen and 78 percent nitrogen.

The temperature on Mars varies wildly. In the summer, near the equator, temperatures can actually reach above the freezing point of water, but the air pressure is so low (just 0.6 per cent of Earth's surface pressure) that water still cannot exist as a liquid, and it wouldn't feel very warm. In winter, at the poles, the temperature can plummet as low as -125 degrees Celsius (-193 degrees Fahrenheit).

So Mars' atmosphere is not a mixture that you can breathe, and the temperatures mean that you would

**"Under such low pressure your blood would boil, so a spacesuit is essential to surviving on Mars"**



The Red Planet is an extremely barren place

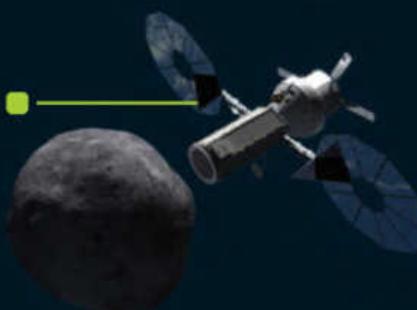


## Landing on a foreign body

Mission length: 1-12 months  
Time to return to Earth: days

### Humans on asteroids

By visiting an asteroid redirected to lunar orbit, we're hoping to expand our manned space exploration capabilities



## Getting ready for Mars

Mission length: 2-3 years  
Time to return to Earth: months

### Manned exploration of the Red Planet

We're aiming to gain planetary independence by landing on Mars, its moons and other deep space destinations

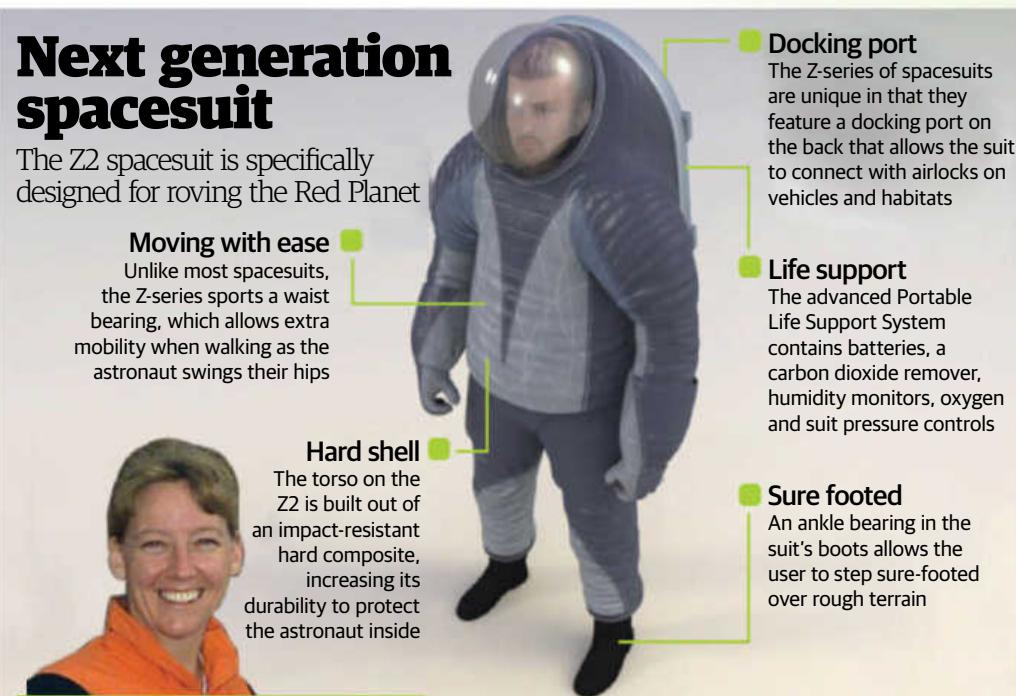
freeze. Not only that, under such low pressure your blood would boil, meaning a spacesuit is essential to survive on Mars. Specially designed suits are in development that will transform any budding space adventurer into a Buzz Lightyear lookalike.

NASA's new Z-series spacesuits are prototypes of what men and women may one day wear when they are trudging around the surface of the Red Planet. The key difference between the Z-series and other spacesuits is that they will be designed to make walking easier, which astronauts haven't really needed to do when floating in space. Even when the Apollo astronauts ventured to the Moon, they only had to put up with an ungainly gait for short excursions onto the surface. When spending 500 days on Mars, the astronauts are going to want to wear something that is practical and flexible, and not as stressful on the human body. The Z-series achieves this by having bearings in the shoulders, waist, upper legs and ankles that allow greater freedom of leg movement and firmer footing. The upper torso of the latest version of the suit - the Z2 - is a hard shell, so if an astronaut tumbles, they are less likely to damage or rip the suit. In Mars' cold, low pressure, unbreathable air, that would be deadly.

The Z-series spacesuits will essentially be life-support systems for the Mars dwellers. Not only do they offer protection against the cold and the poisonous atmosphere, they also provide air, water and even food, and monitor the astronaut's health. Scientists at NASA's Johnson Space Center are currently working on an advanced Portable Life Support System (PLSS) that will attach to the Z-series suit. The PLSS will control the suit's pressurisation, as well as remove poisonous carbon dioxide that has been exhaled by the astronaut, which would otherwise build up in the suit's air recycling system.

## Next generation spacesuit

The Z2 spacesuit is specifically designed for roving the Red Planet



### SPACESUIT DESIGNER

#### Amy Ross, NASA

"The Z-series spacesuit is designed with very good walking capabilities. I participated in the spacesuit field-testing, where we wanted to understand what a suit that we built for the Moon or Mars would be like doing its job, and the only way to do that is to go out and see. How does the subject in the suit do geology for instance? We monitor how well the suit allows them or doesn't allow them to do that job,

and what features we need to focus on for further development. The strategy we're taking right now is looking at what the most challenging aspect is. For mobility on Mars, it is being able to walk on the surface. We try to design so that we're capable of that, so when we have to build a suit for one specific mission, we already have the information and capability to build a spacesuit that's going to work."



The importance of a safe spacesuit becomes clear once you look at what would happen should you become exposed to the Martian air. Imagine you are on that first human mission to Mars. You open the airlock, climb down the ladder and put that first booted footprint into the Martian dust. You step out and go for a short walk around the landing site. Unfortunately you have landed close to a gorge. Unaccustomed to the low gravity, you fall in, smashing your helmet's visor on a rock (in reality, a spacesuit's visor is extremely tough and would be hard to break). The oxygen in your helmet quickly leaks out and within 15 seconds you lose consciousness from the lack of oxygen. The low pressure causes your blood to boil, making your skin and organs expand. Your body becomes swollen, but your blood does not evaporate - instead as it boils it sheds heat quickly and, in the cold temperatures of Mars, actually freezes. The low pressure and lack of oxygen will kill you in less than a minute.

Another scenario is that one of your suit's air valves might develop a small but deadly leak. You probably won't hear the air whistling out through the hole, as the thin atmosphere muffles sound, but the PLSS on your back will alert you to the fact that your oxygen and pressure is decreasing, while carbon dioxide leaking in from outside is building up, slowly suffocating you. Fortunately, air valves, tubes and other life support fittings will be standardised not only on the suit, but where possible in the habitat and any vehicles, making repairs relatively simple.

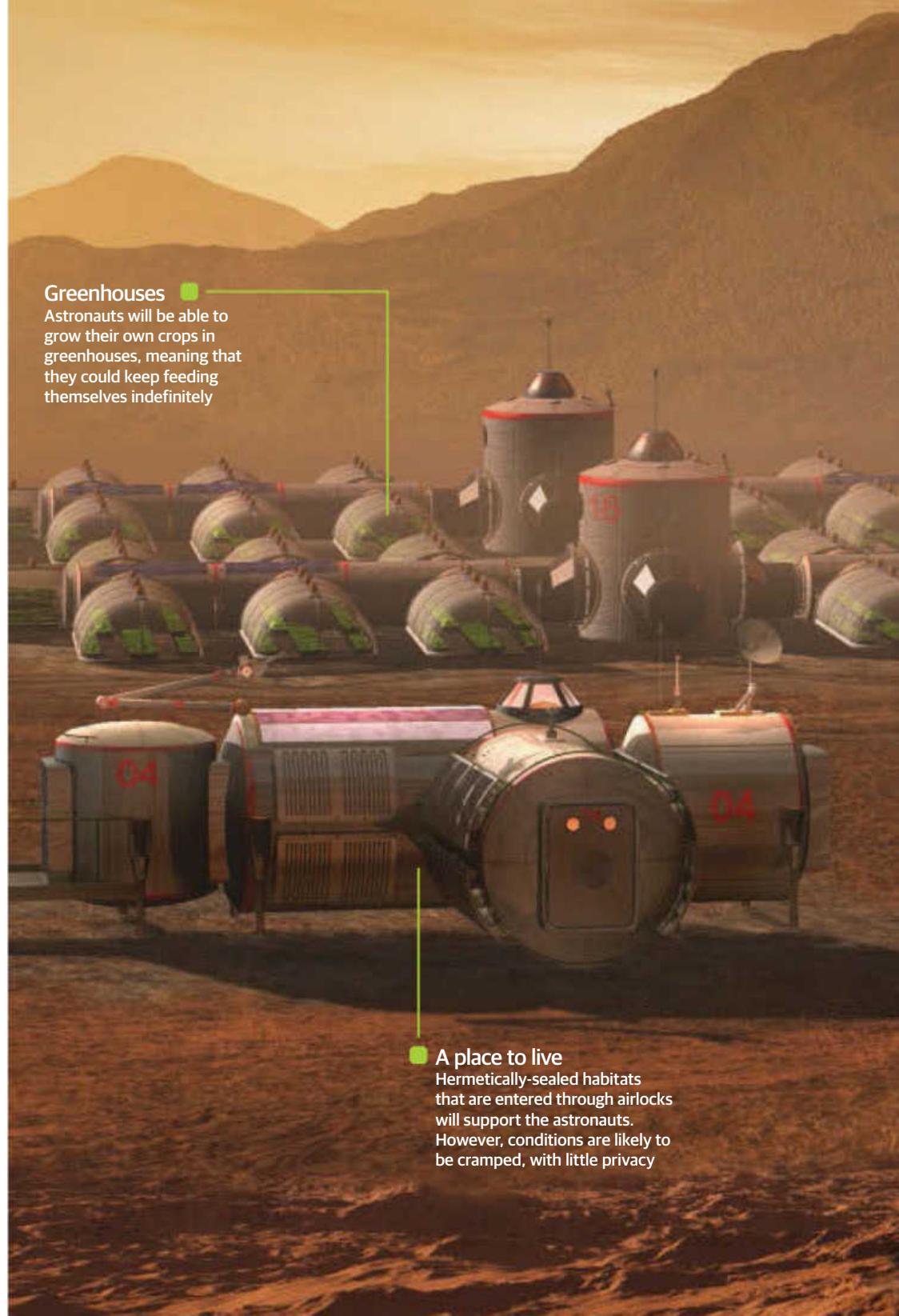
A nifty feature of the Z-series suit is that the astronaut enters the suit through a port at the back - that same port can be used to 'dock' with vehicles or even habitat buildings and allow safe passage inside from the suit. In many ways, a Mars habitat will be an extension of the life support system of the spacesuit. It will need to keep the astronauts safe and comfortable for 500 or more days without being resupplied, and with only limited repairs possible should damage be incurred. The habitat could be hit by dust storms or even a meteorite fall - as the atmosphere is so thin on Mars, more meteors are able to reach the surface intact than on Earth.

As discussed earlier, the habitat is likely to be made from crew modules that landed on the surface during the pre-cursor flights. However, an alternative method would be to print and assemble a habitat on Mars using a 3D printer. NASA has commissioned dozens of plans and designs of habitats in the past for use on both Mars and the Moon. For example, scientists in the Aerospace Engineering Sciences Department at the University of Colorado produced a report on the engineering design of a proposed Mars habitat, highlighting that each life support system needs several layers of redundancy. For example, if the water recycling system or the power generator breaks down, a back-up would be available to step in, and there would be a back-up for the back-up too.

A Mars habitat also needs to be capable of providing food. Surprisingly, scientists believe that Martian dirt would be suitable for growing crops in. Dutch scientists have tried this in their laboratory, by making their own 'Martian dirt', based on what the Mars rovers and the older Viking missions of the 1970s have taught us about its composition. The 14 species of plant grown in the Martian dirt

# Living on another world

Turning the Red Planet into our home will involve many adaptations and alterations





### Hidden danger

The pink sky on Mars looks calm and serene, but with the onset of Martian summer, huge dust storms can blow up that turn the sky dark and cover solar panels

### Phoning home

Talking with mission control or loved ones back home will be difficult for Mars astronauts. Because our two planets are so far away from each other, a signal will take up to 20 minutes to reach from one planet to the other

### MARS EXPERT

## Bob Zubrin, Mars Society

"The basic idea is to explore Mars with a 'travel-light' philosophy, so rather than building giant spaceships in orbit loaded with all of the food, water, air, fuel and oxygen required for a round-trip mission, we try to make the most important of these on Mars. First you'd send a Mars return vehicle with no one in it. That lands on Mars and reacts a small amount of hydrogen that it brought from Earth with carbon dioxide in the Martian atmosphere to produce a large supply of methane, oxygen rocket propellant and oxidiser. So now you have a fully fuelled Earth-return vehicle sitting on the Martian surface. Then you shoot the crew out to Mars in a habitation module that they use as their house while they are on Mars exploring. Then after 18 months of exploration they get in the Earth-return vehicle and fly back, leaving the habitation module on Mars. Each time you do this you add another habitat to the base and before you know it, you have the first human settlement on another world."

### Low gravity

The gravity on Mars is just 38 per cent of the gravity on Earth. Astronauts will have to get used to living and working in this low gravity for months on end



09

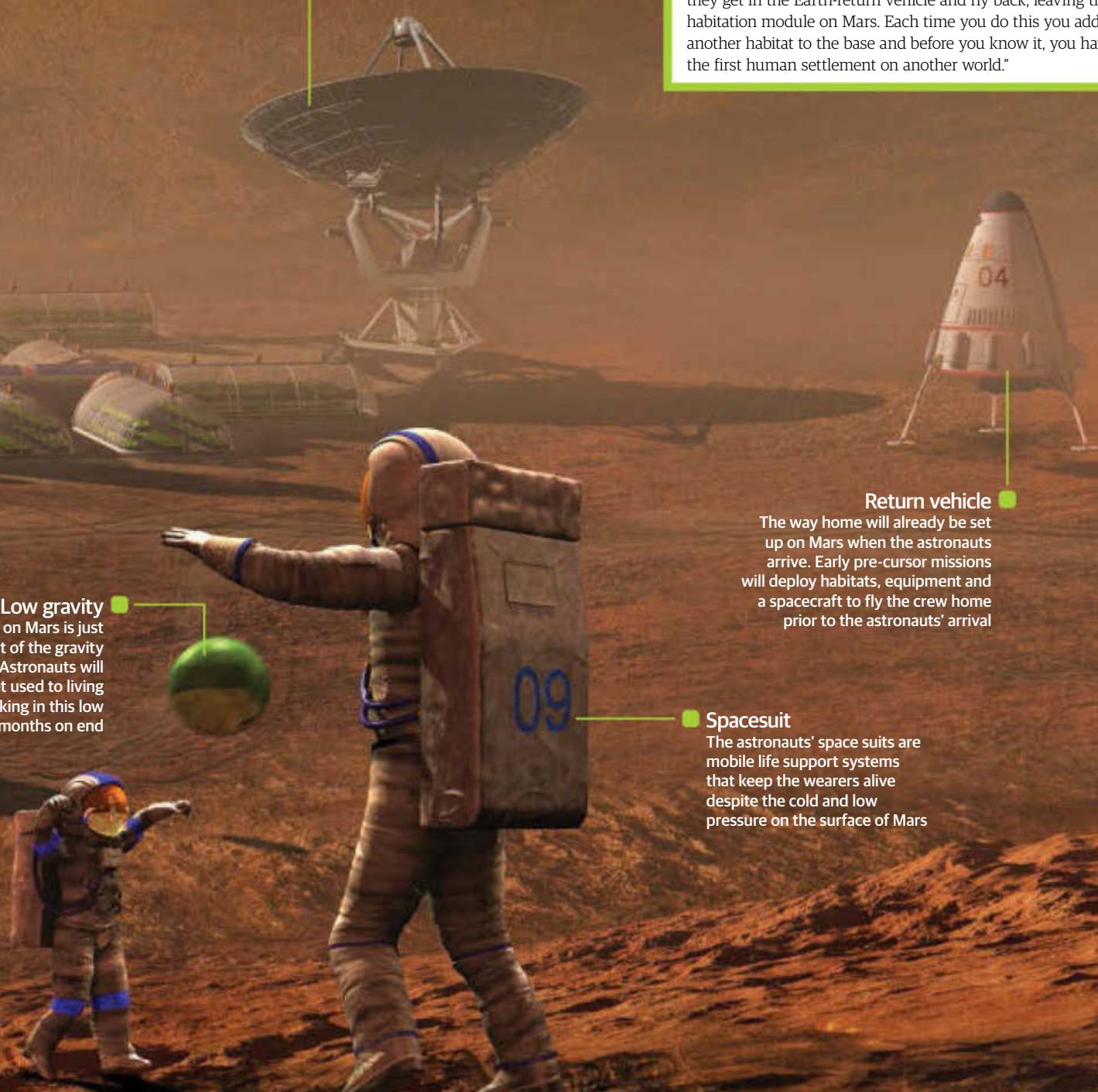
### Return vehicle

The way home will already be set up on Mars when the astronauts arrive. Early pre-cursor missions will deploy habitats, equipment and a spacecraft to fly the crew home prior to the astronauts' arrival



### Spacesuit

The astronauts' space suits are mobile life support systems that keep the wearers alive despite the cold and low pressure on the surface of Mars





## MARS MISSION EXPERT

### Steve Squyres, NASA

"Despite having devoted my career to exploring the Solar System with robots, I am a strong advocate of human exploration, particularly on Mars. Humans have an extraordinary ability to function in complex environments, to improvise, and to respond quickly to new discoveries. Robots, in contrast, do best when the environment is simple and well understood, and when the scientific tasks are well defined in advance. The capabilities of humans surpass those of robots in complex environments. And there is no planetary environment where humans can operate in the foreseeable future that is more complex than the Martian surface."

replica flourished; they germinated, flowered and survived the 50 days that the experiment lasted. Dirt on Mars lacks nitrogen and liquid water, which plants need, but contains many other nutrients that plants can feed from. The introduction of bacteria into the dirt can provide a source of nitrogen, and the humble watering can will supply the water. Future Mars habitats will therefore have a greenhouse section where crops are grown. These will have to be artificially lit, as the daytime Sun on Mars is fainter than it is on Earth. Nevertheless, starvation should not be a problem for the Mars population.

Obtaining water should be a simple task too. Mars is a dry world, but there is plenty of water on it, in the form of ice. There are the ice caps at the poles, but there is also subsurface permafrost ice just below the surface, stretching down to the planet's mid-latitudes. So water could be obtained by melting this ice. Another option is to copy the stranded astronaut in *The Martian*, who burns hydrazine rocket fuel to release hydrogen, and combines this hydrogen with oxygen produced by his habitat's 'oxygenator', which splits oxygen from Mars' carbon dioxide atmosphere.

A habitat will also act as a shelter to the elements outside. Mars has no global magnetic field and a thin atmosphere, so it cannot deflect solar radiation. The habitat will contain a shielded room to protect from the radiation emitted by solar flares. Unfortunately, the astronauts will need to rely on fate or good luck to protect them from cosmic rays while out and about on Mars - prolonged exposure out in the open will increase the chances of the astronauts getting cancer from space radiation.

The biggest natural hazard on Mars is the wave of dust storms that blow up every Martian summer. The biggest ones can envelop the entire planet, coating

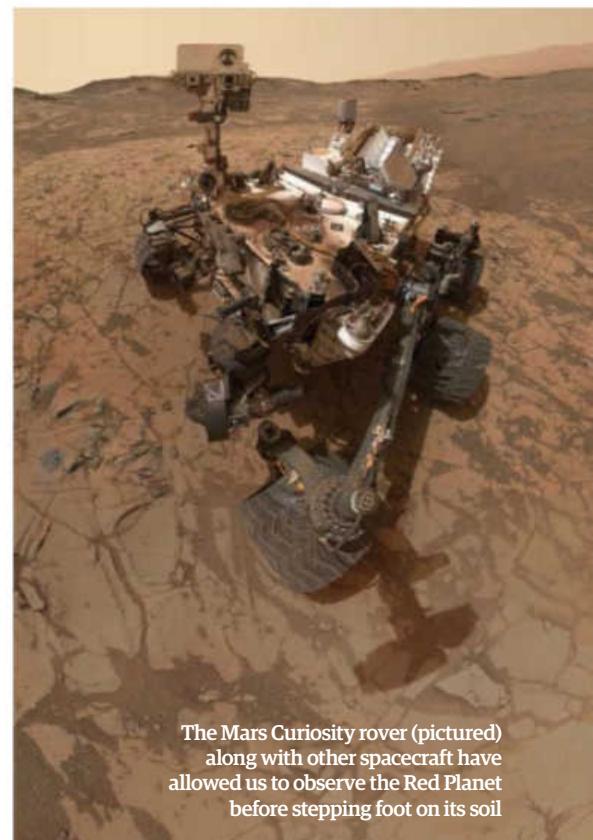
solar panels with dust and concealing the Sun in the sky. Martian dust is made of very small particles, and the wind speeds are not very high in the thin atmosphere. So a habitat is not going to be blown over in a storm, but it is possible that the dust could find its way into the living area or into electronics, causing serious damage. However, the Mars Rovers have survived many dust storms; the biggest problem they faced was a loss of power as their solar panels became covered in dust. Fortunately, astronauts can just wipe the panels clean.

The biggest obstacle to surviving on Mars may not be the lack of air, or the cold, radiation or planet-sized storms. The biggest killer could be loneliness. Even if you are stranded alone like the hero in *The Martian*, and you are with six to ten other astronauts, you are still 200 million kilometres (124 million miles) from your friends, family and everything you knew on Earth. Your calls to home will take 20 minutes to get there, and then another 20 minutes to be returned. Scientists are attempting to study how long-term exposure and isolation in space affects mental health - the year-long mission of NASA astronaut Scott Kelly on board the International Space Station is part of this research. Spending over two years in a challenging and alien environment will tax even the most mentally strong - unlike a mission to the Moon, you can't be back home in three days.

Astronauts travelling to explore Mars are going to need to be tough, both mentally and physically, and well prepared for the challenges that meet them. However, with scientists and engineers back on Earth supporting their mission, years of intensive training to help them, and a knack for ingenuity and adaptation, perhaps it will be possible to survive on Mars after all. ●



The team behind NASA's Mars Science Laboratory



The Mars Curiosity rover (pictured) along with other spacecraft have allowed us to observe the Red Planet before stepping foot on its soil

# Mars One roadmap

How a private organisation plans to be the first to land man on Mars

**2016**

## Mars on Earth

After its selection of 40 astronauts, Mars One intends to simulate Mars' conditions at multiple locations on our own planet, including the Arctic



**2022**

## Rover exploration

Exploration of the Red Planet is essential before Mars One can send humans to its surface.

By 2020, the organisation intends to send a rover to Mars

**2026**

## Mars One send first astronauts

In 2026, the components of the Mars Transit Vehicle will be launched to Earth orbit after receiving the green light on the status of the systems on the Red Planet



**2027**

## First astronauts land on Mars

Approximately 24 hours before landing, the crew will move from the transit habitat into the landing module, bringing some supplies with them. The landing module will then detach from the transit habitat, which is too large to land on Mars

**2024**

## Cargo mission launch

A second rover, two living units and a supply unit will be sent to Mars ahead of the astronauts. By 2025, it's hoped that all units will land on Mars using a rover signal as a beacon



## One-way ticket to Mars

We talk to two Mars One candidates, who have been selected to face the challenges of the Red Planet

### What training will you need to be able to survive on Mars?

**Ryan McDonald:** Perhaps the most important aspect of training is spending up to three months each year conducting a mission in one of the simulation outposts. During these simulations we are continually subject to surprises, obstacles and intensive struggles with the intention of ensuring that only the most committed stick through to the end, since there is no turning back once you are on Mars.

**Hannah Earnshaw:** We will need to have all the skills necessary to run the settlement ourselves, as well as to respond to any emergency without help from Earth as a message could take up to 40 minutes to receive a reply. We will need training in engineering, farming and medicine, as well as research skills and even knowledge of administration and governance of a settlement, as we grow beyond a small group of pioneers into a fully functioning town.

**RM:** To gain those skills we go through an intensive technical study programme, during which two members in each crew specialise in engineering and two in medicine. We also have to spread between ourselves disciplines as diverse as dentistry, exobiology, geology and atmospheric physics, to name a few. This is part of the reason why the training takes at least ten years, since there is a huge quantity of material to cover.

### Are you comfortable with the risk involved?

**HE:** Any mission involving leaving Earth involves danger, and Mars One is no different. You have to get comfortable with the idea that you might die if something goes wrong in space. In the knowledge that every effort will be made to keep us safe, I think that the value of space missions, especially a Mars settlement mission, is worth the risk to my life. Of course, the last thing that Mars One wants to do is send anyone to Mars who isn't absolutely willing and committed to go. So we all have the option of backing out of the mission right up until launch day if we change our mind.

**RM:** You have to accept that this is not a safe mission. The risk of catastrophic failure is around 2.5 per cent - similar to climbing Everest. The amount of radiation we will be exposed to during the flight to Mars coupled with the exposure during surface operations will raise our risk of fatal cancer by one to three per cent over our lifetime. The selection committee ensures we are clearly aware and accept the risks during the interview stage.

### What will be the greatest danger on Mars?

**HE:** The greatest danger will be the unexpected. We have a good handle on the levels of radiation we will be exposed to, the effect of dust storms on solar panels and so on. It will be freak accidents, broken equipment, uncharacteristically extreme weather or



## MARS ONE CANDIDATES

### Hannah Earnshaw

Earnshaw is a PhD student at Durham University. Space travel is a lifelong dream for her and she is one of five Britons shortlisted by Mars One for a one-way ticket to Mars.

### Ryan MacDonald

Another Briton selected to make the journey to Mars, MacDonald has recently completed his Master's degree in Physics at Oxford University and is soon to be studying exoplanets at Cambridge University as a PhD student.

other things that we cannot predict that we will need to be able to respond to quickly and creatively in order to survive.

**RM:** The final descent to Mars is statistically when things are most likely to go wrong. This can be mitigated by using the same automated landing system for the human landing as the eight prior robotic missions, leading to reasonable trust in the reliability of the system. It's worth noting that Neil Armstrong's piloted touchdown on the lunar surface was never tested in a lunar environment before being used for the Apollo 11 landing, so this approach of eight prior vetted landing successes makes Mars One's entry, descent and landing process substantially less risky in general.

# JUPITER PLANET KILLER

From its impact on Mars to the destruction of super-Earths, did the gas giant greatly influence the Solar System as we know it?



There are many things we know about Jupiter. It is a huge gas giant with a mass equivalent of 317.8 Earths. It is twice as massive as every other planet in the Solar System combined. It has four large moons and a number of smaller ones, and it spins at an incredible rate, which means a day lasts less than around ten hours.

But there are also some things about Jupiter, which continue to surprise us. Who would have thought, for example, that this mass of hydrogen and helium could potentially have been a wrecking ball, helping to shape the entire Solar System as we know it today?

As it stands, the eight planets appear to be in regular, fixed orbits around the Sun. Mercury is closest, followed by Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune. Yet it wasn't always so and, while everything appears to be in order now, there are some anomalies which have niggled away at astronomers for some time.

One of these issues is Mars. Whenever scientists have tried to use computers to model the formation of the Solar System's four innermost planets, the mass of the Red Planet has either showed as being up to ten times greater than it actually is or much closer to the Sun. Something, they pondered, must have killed Mars' chances of growth and altered its orbit. And that something, some astronomers say today, was Jupiter.

Over the years, various studies have tried to come up with an explanation for the problem. In 2009, Brad Hansen from the University of California, Los Angeles (UCLA), put forward the theory that solid material in the Solar System was only distributed up to a certain point. He claimed there was a boundary of one Astronomical Unit (AU) from the Sun, after which planets would struggle to gain enough material in order to grow in size.

This idea worked well: one Astronomical Unit is the distance between the Earth and the Sun and it would explain why our home planet and Venus are far larger than Mars. Since Mars is situated at 1.5AU from the Sun, it would fall outside of the boundary set by Hansen. That would leave Mars with less solid material from which to build and it sounded like a perfect explanation. Yet a key element was missing. "Hansen did not explain how it could be, he just assumed [the position of the boundary]," says astronomer Alessandro Morbidelli. It did not account for the gas planets and the asteroid belt falling well outside of the 1AU boundary. "How could that be?" questioned Morbidelli.

He, along with Sean Raymond, Kevin Walsh, Avi Mandell and David O'Brien, started to look more closely at Jupiter, the largest planet in the Solar System, in order to explain the low mass of Mars. They eventually came up with the Grand Tack Hypothesis, which proposed that a lonely Jupiter was the first planet to form and that it had moved twice over its lifetime: firstly heading inwards towards the Sun and then migrating outwards into the position it occupies today. This is where things become rather interesting. "We knew that for a small Mars, we needed to have a deficit in the planet's feeding zone," says Raymond, an astronomer at the Laboratoire d'Astrophysique de Bordeaux in France. "It's a pretty basic idea that for Mars to be small, it

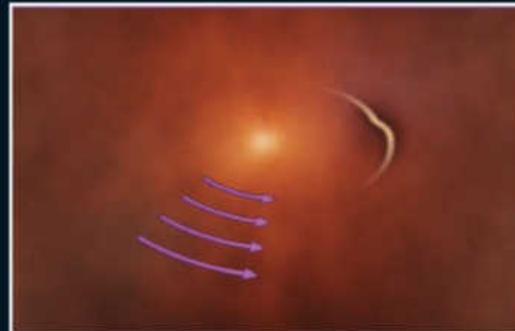
# The making of gas planets

How worlds like Jupiter are formed could be down to one of two theories

## Bottom-up model

### 1 The start of a planetary system

Dust grains in orbit around a young star begin to coalesce into planetesimals. The clumping occurs through non-gravitational forces.



### 2 Growing into planets

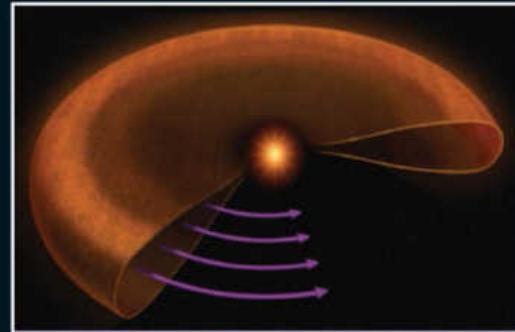
The size of the planetesimals begins to increase, moving in orbits, to form the planetary embryos.



## Top-down model

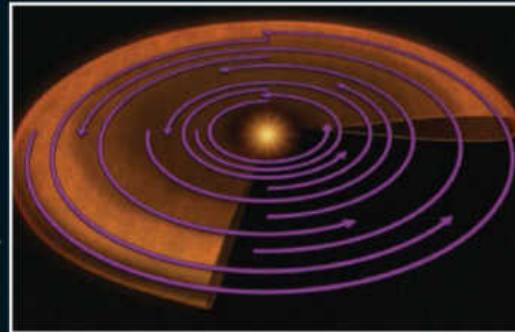
### 1 In the beginning

A disk of gas and dust – known as a protoplanetary disk – is made around a young central star.



### 2 Unstable dust

Gravitational instabilities in the disk form clumps of gas become a planet by self-gravitation.



had to be starved whereas Earth and Venus were not. So we thought, what about Jupiter; what if it had been sitting where Mars currently sits?"

They posed that Jupiter travelled through the inner Solar System from an initial position of 3.5AU to 1.5AU, which is more or less Mars' current orbit. It was pulled inwards by the gravity and currents of the thick gas of the protoplanetary disk, which surrounded the young Sun in the early days of the Solar System's history. The dense gas of this disk prevented it from getting too close and falling into our star but, crucially, it meant that Jupiter absorbed a lot of debris that had existed in that region and this would have had a profound effect on the way the Red Planet would subsequently develop.

At this stage, none of the terrestrial planets had formed. Mercury, Venus, Earth and Mars are younger than the gas planets and they were born much later. The Grand Tack scenario - which would have taken place during the first ten million years of the Solar System's existence - supposes that Saturn followed Jupiter in migrating towards the Sun and that the pair entered into orbital resonance. This meant both

Saturn and Jupiter exerted a regular and periodic gravitational influence on each other which resulted in a cosmic dance, pushing all of the gas between them out and eventually seeing the two gas planets migrate back out towards the outer Solar System.

Jupiter eventually reached its current position of 5.2AU, but because it had absorbed much of the debris in its former position in Mars' orbit, it had effectively caused the Red Planet's growth to be stunted, killing its chance of becoming as large as Venus and Earth. What's more, since Jupiter had not gone beyond 1.5AU, it had not affected the debris closer to the Sun. That meant the three innermost terrestrial planets - Mercury, Venus and Earth - were able to form as expected.

To see how this affected Mars, you need only compare it to Earth. Both rapidly generated mass at the start of their planetary lives but while Earth continued, Mars did not. Although Mars is believed to have formed around 1AU and was able to amass its core, gravitational interactions which pushed it out to its position at 1.5AU ensured it was in a region which lacked enough debris to allow it to grow. Mars was

therefore forced to stop growing far earlier than our own planet.

"The timescale for the formation of Mars is much shorter than for Earth," explains Morbidelli, who adds that the Earth formed 50 per cent of its mass in the first five to ten million years. "Earth took 100 million years and Mars took four million years. So at the beginning, Mars created mass and then it suddenly stopped. This idea of Jupiter depleting the region and then leaving little behind can explain the mass of Mars and explain why the creation of Mars was aborted so quickly."

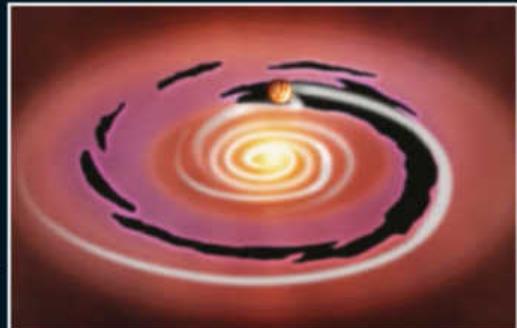
Not that this is the end of Jupiter's potential role in shaping the way the planets around us formed. Some scientists believe super-Earths once existed in the Solar System and that these planets - which are up to ten-times the mass of our own yet smaller than Neptune - once existed close to the Sun just as they do in many other planetary systems. They helped to form what could be termed a Solar System 1.0 as opposed to the second version so familiar to us now but they may well have been destroyed by an all-conquering, migrating Jupiter.

It sounds fanciful but this is the theory put forward by Konstantin Batygin, a planetary scientist at the California Institute of Technology, and Greg Laughlin, an astronomer at the University of California, Santa Cruz. Their idea incorporates the Grand Tack Hypothesis and it was inspired by the results of the Kepler Space Telescope mission, which

**"The idea is that, if our Solar System was like others, then we should have had a number of super-Earths"** **Greg Laughlin**

### 3 The making of a gas giant

Before the gas in the disk disappears, the planetesimals drag gas envelopes onto themselves that gives them their puffy layers.



### 4 Planetary scatter

Some of the gas giants scatter and, due to their sheer size, accrete remaining planetesimals and embryos.



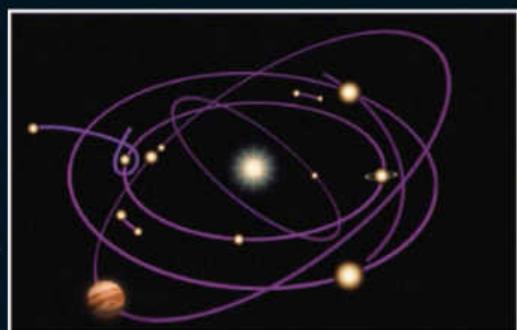
### 3 Forming the centre

Grains of dust clump together at the centre of the young world, known as a protoplanet, to form a core.



### 4 Collecting gas

The protoplanet sweeps out a wide gap from the disk, feeding on the gas that it draws onto itself.



Showed that the average stars in the galaxy are closely orbited by a couple of rocky planets more massive than Earth with thin atmospheres.

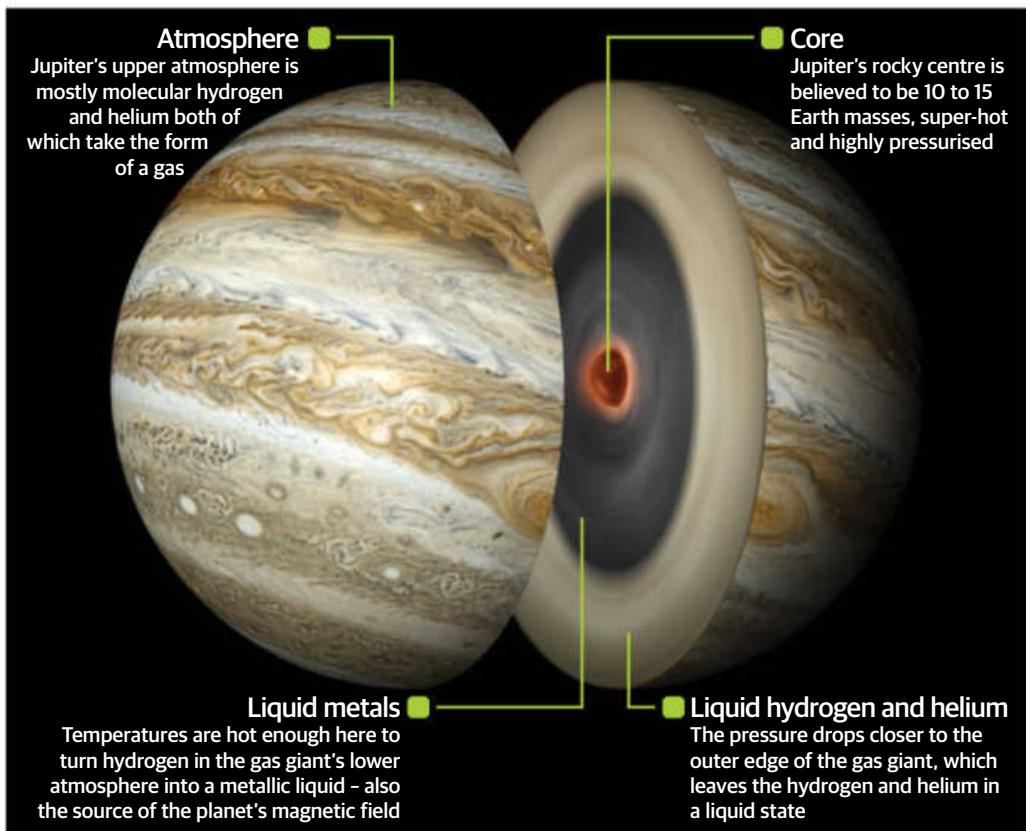
"What Kepler pointed out was the inner part of the Solar System is just plain missing," says Laughlin, who also notes that giant gas planets in other planetary systems are often just one-tenth of the distance between Mercury to the Sun. "That really got us thinking about how the formation of Jupiter and how the Grand Tack could perhaps have cleared out the inner Solar System. The idea is that if our Solar System was like others, then we should have had a number of super-Earths in a short period of orbit." But if this was the case, then they would have to explain where these super-Earths had gone.

Batygin and Laughlin proposed that super-Earths were created before Jupiter migrated forward. "The earliest phase would have been a rapid formation of super-Earth planets," asserts Laughlin. "They would have had access to a lot of material because the surface densities are high, and because they had a short period of orbit which means it doesn't take long for them to go around the star, they would have formed quickly."

When Jupiter set off towards the Sun as proposed in the Grand Tack Hypothesis, Batygin and Laughlin say it forced the super-Earths into overlapping orbits. This caused them to collide and break up, and it meant, as Laughlin explains, that the super-Earths were "thwarted at their first attempt by Jupiter's

### Atmosphere

Jupiter's upper atmosphere is mostly molecular hydrogen and helium both of which take the form of a gas



### Core

Jupiter's rocky centre is believed to be 10 to 15 Earth masses, super-hot and highly pressurised

### Liquid metals

Temperatures are hot enough here to turn hydrogen in the gas giant's lower atmosphere into a metallic liquid - also the source of the planet's magnetic field

### Liquid hydrogen and helium

The pressure drops closer to the outer edge of the gas giant, which leaves the hydrogen and helium in a liquid state



## Beyond Earth

"inward migration". It also put the gas giant in an orbit typical of many other planetary systems. "Jupiter would have triggered this collisional cascade in which all of the bodies that were trying to form in the region where Earth is now would have started colliding, bashing each other up and fragmenting," continues Laughlin.

The effect of this was to push the debris of the super-Earths into the Sun as it spiralled down under gas drag which cleared out the region between the Sun and Mercury, accounting for why there is very little debris there. If proven, this theory will help explain why the Solar System became so unlike scores of other planetary systems and why the terrestrial planets we have today are so much smaller. It allowed a first generation of planets to be destroyed and allowed for a second wave of smaller, mass-depleted replacements.

"A sort of unrealised consequence of the Grand Tack is that it would have acted as a wrecking ball and screwed up the configuration of planets that was originally there," says Laughlin on the theory. "Then Jupiter and Saturn moved outward once they were caught in resonance and eventually the Earth and the other terrestrial planets formed out of the debris that was left from Jupiter's kind of inward and outward movement."

He says this is why the terrestrial planets are younger than the giant gas planets. They were only able to form once Jupiter had smashed the previous planetary bodies out of the way. "It points towards a framework where we can understand the effect that the terrestrial planets are younger than the giant planets even though they should have had the advantages to get a head start through access to material on the one hand and especially fast-running dynamical clocks on the other hand," says Laughlin.

It makes for a rather odd Solar System and it shows the disruption that Jupiter managed to cause so early on. "The indication that we're giving so far is that the Solar System has some curious and unusual features," explains Laughlin.

"A giant planet like Jupiter in a near circular orbit is not something that happens in every Solar System

**Observations by the Kepler space telescope show that many gas giants in other solar systems orbit much closer to their parent stars than Jupiter does**



and, in fact, it is something that happens in probably just a couple of per cent of solar systems. A total lack of anything inside Mercury's orbit is very unusual and it could well be that because the terrestrial planets formed later they didn't have access to the gas-rich nebula that they would have had if they had formed in the normal course of events.

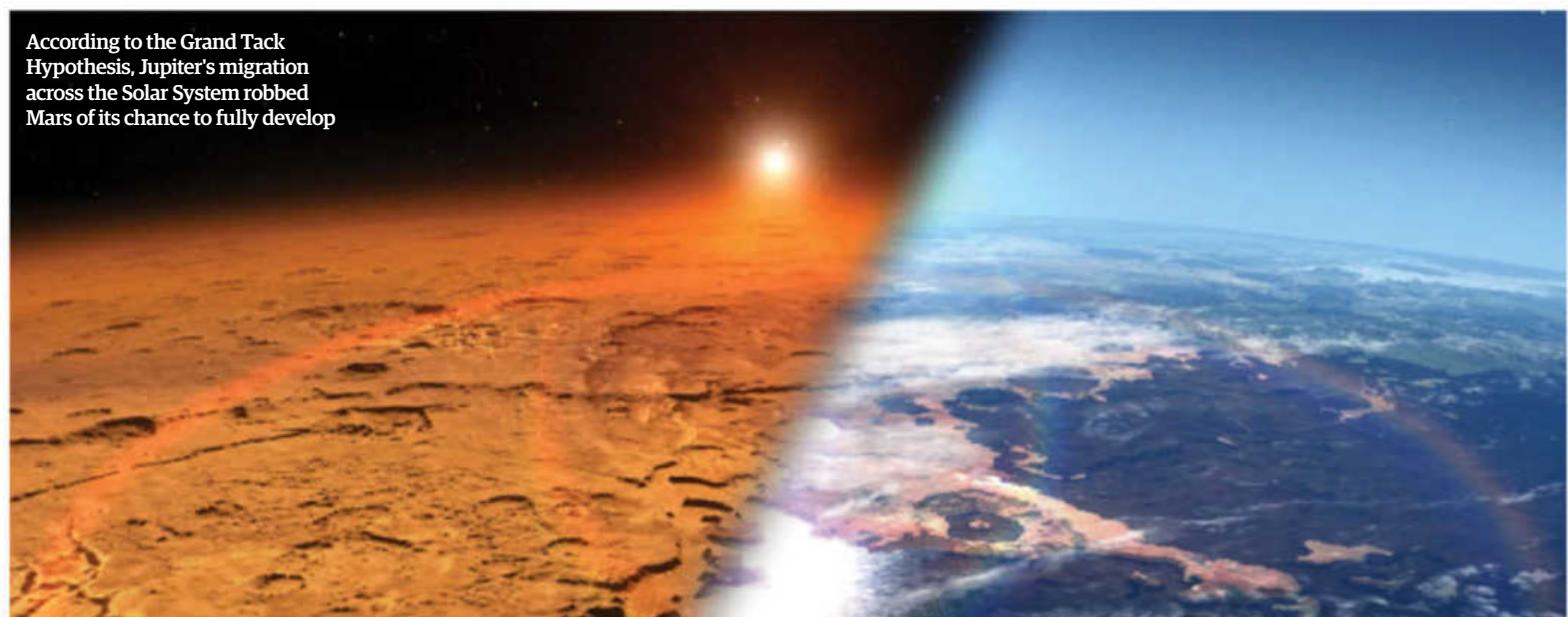
"That could mean that planets with solid surfaces and atmospheric pressures similar to our own might be relatively rare. Now that's a speculation, but I think it's okay to make speculations that point towards cautious, conservative, less-than-exciting interpretations because there is just an abundance of wide-eyed speculation about life on other planets and so forth so the fact our Solar System gives a more sobering extrapolation I think is okay to make that."

Even so, Morbidelli is unconvinced that super-Earths did exist in the Solar System. He considers

Batygin and Laughlin's work to be young, with aspects that still need investigating. He says the protoplanetary disks have an inner edge beyond which planets could not go. "There are forces which retain the planets at the edge," he says, "and these forces will push against the dust." For that reason, they could not migrate into the Sun. There are also those who refute the Grand Tack Hypothesis, and if it was proven it would have huge ramifications.

"It would make the Solar System special again," says Morbidelli. "It would show that we are really here because of a sequence of specific events and it is obvious this does not happen all the time. If Jupiter had migrated later, for instance, then we would not be here because Earth could have been the size of Mars. Don't get me wrong, I'm not saying it is unique and we have had the hand of God to make it but it's a sequence of events that is not most frequent." ■

**According to the Grand Tack Hypothesis, Jupiter's migration across the Solar System robbed Mars of its chance to fully develop**



# Timeline of events: How the king killed planets

Jupiter's possible migration in and out of the Solar System would have had a major long-lasting effect

## 0 years

### Jupiter forms

In the early Solar System, thick gas and dust orbited the Sun in the protoplanetary disk. Jupiter was first to form within the protoplanetary disk at a distance of 3.5 Astronomical Units (AU).

## 70,000 years

### A major attraction

Jupiter accretes gas from the disk, allowing it to become a gas giant. A massive gap opens in the disk and the planet then began to migrate inwards towards the Sun.

## 80,000 years

### Super-Earths smashed

One theory claims Jupiter collided with super-Earths, formed close to the Sun. Debris spiralled into the Sun although sufficient material was left behind to form the terrestrial planets we see today.

## 100,000 years

### Saturn forms

Saturn formed before Jupiter's migration at 4.5AU. When close to its current mass, its gravitational interaction with the gaseous component of the protoplanetary disk made it migrate inwards too.

## 120,000 years

### The gas giants get close

As it was pulled in by gas cloud currents, Saturn got close to Jupiter. The planets entered an orbital resonance with each other. For every two orbits of the Sun Saturn made, Jupiter made three.

## 300,000 years

### Outward migration

At this stage, Jupiter had settled at 1.5AU, the same orbit that Mars now occupies. Jupiter tacked, meaning its migration reversed. Both it and Saturn began migrating outwards, away from the Sun.

## 500,000 years

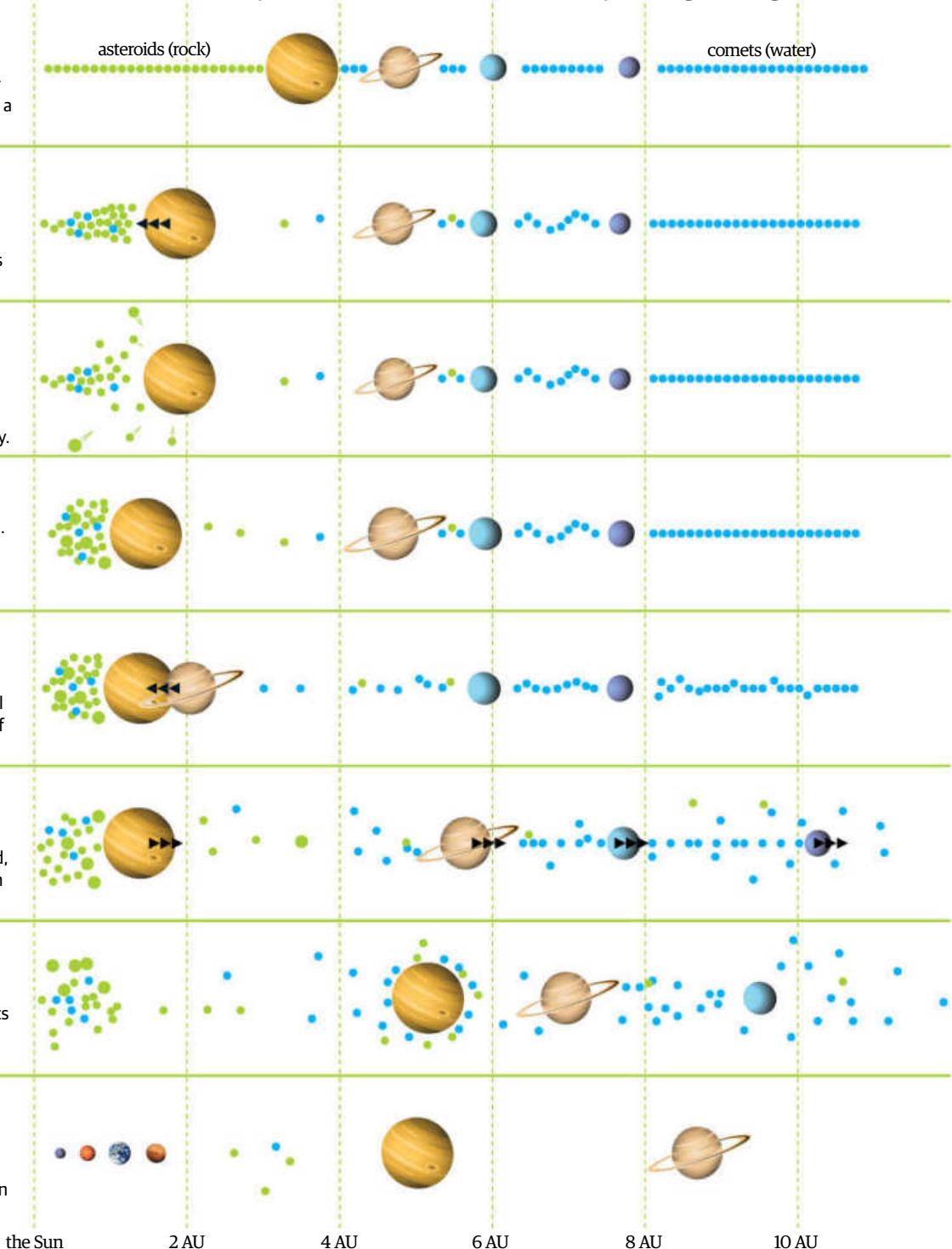
### Sweeping up asteroids

As the planets migrated outwards, Jupiter swept aside 15 per cent of asteroids it met, as it had on its way in. This explains why there are two classes of asteroid and the asteroid belt mass deficit.

## 600,000 years

### Jupiter settles

Jupiter settled on the orbit it now occupies at 5.5AU as outward migration slowed and the disk ran out of gas. Uranus and Neptune were caught in resonance. The planets had obtained full masses.



@ Tobias Roetsch; Alamy; Nicholas Forder; NASA freepik.com

## The evidence

### Mars is smaller than expected

When the Sun's protoplanetary disk is simulated on a computer, it shows Mars as larger than it is due to a greater level of mass near the planet's orbit. The Grand Tack Hypothesis supposes Jupiter absorbed much of this mass.

### The asteroid belt's object mix

The existence of icy objects and dry, rocky objects within the asteroid belt has challenged astronomers. The Grand Tack claims Jupiter's outward migration pushed the belt in, and deflected icy objects toward the Sun.

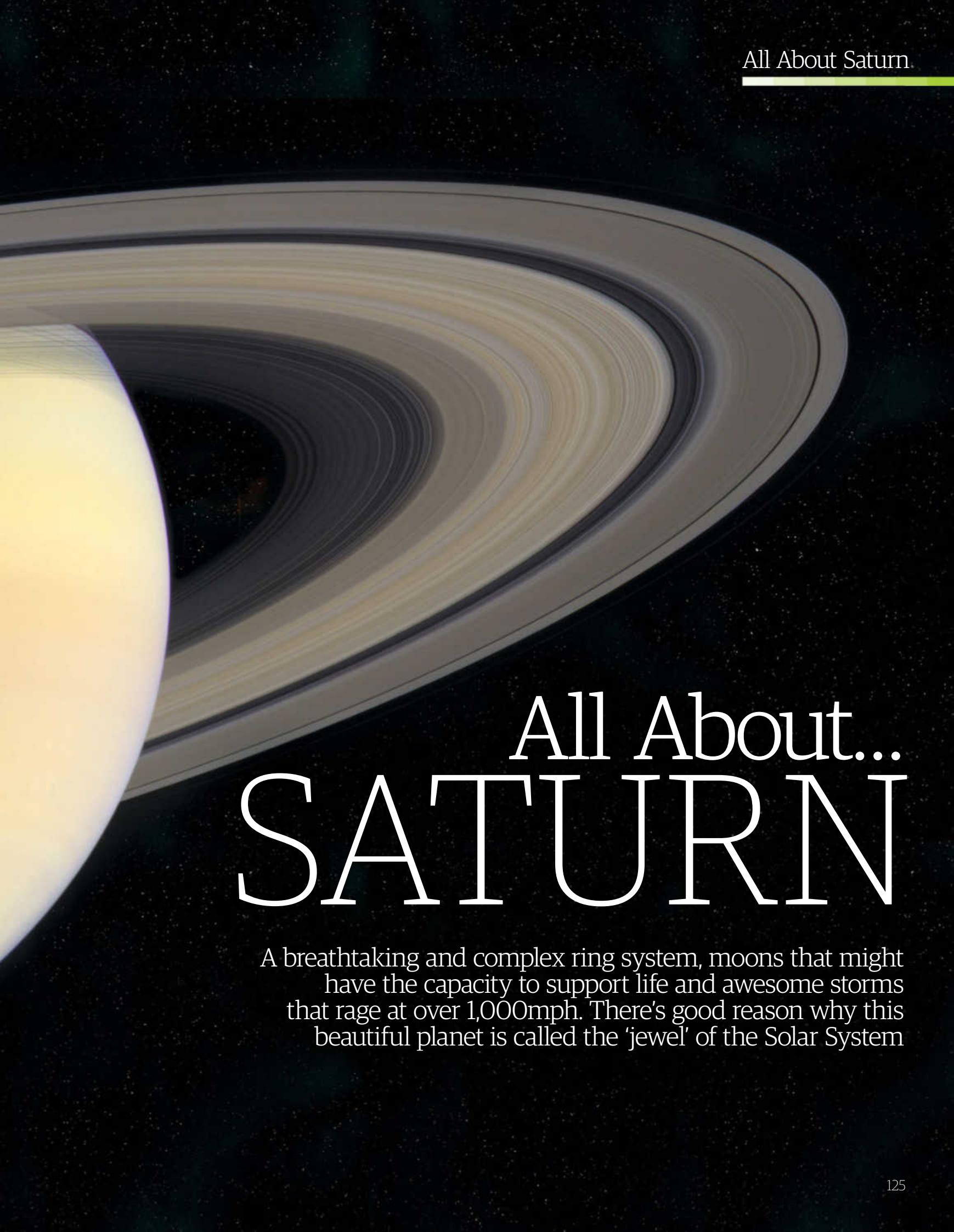
### Earth has the "right" amount of water on its surface

The classical model of the Solar System's formation shows Earth with too much or too little water. The Grand Tack supposes C-type, icy asteroids were the source of water.

### The asteroid belt doesn't have as much mass as it should

The expected mass of the asteroid belt is higher than it actually is. When Jupiter is thought to have drifted into the asteroid belt and back out again, it reduced the mass to the current level.





# All About... SATURN

A breathtaking and complex ring system, moons that might have the capacity to support life and awesome storms that rage at over 1,000mph. There's good reason why this beautiful planet is called the 'jewel' of the Solar System

Gas giant Saturn is the second-largest planet in the Solar System behind Jupiter and the sixth planet from the Sun. As such, it is the most distant planet that is easily visible with the naked eye from Earth. From here, it looks like a bright yellowish point. That doesn't mean that you'll be able to see the rings, though - you will need at least some strong binoculars if you hope to see them.

Saturn is more than 95 times more massive than the Earth, although it has just one-eighth the density. In fact, with a density of just 0.687 grams per cubic centimetre (0.397 ounces per cubic inch), it is less dense than water, meaning that it would float in an ocean if there were one big enough to hold it. Saturn is often compared to Jupiter; the two planets have similar compositions, and both have systems of cloud bands with storms that take place on the surface - although Jupiter's dark areas are much darker and its storms are much more frequent and severe than Saturn's. It's almost like Saturn is a smaller, blander version

of Jupiter - but then there are those fascinating rings.

Saturn has become known as the 'jewel' of the Solar System for its appearance. But it didn't gain that moniker until we began to learn about the rings. Italian astronomer Galileo Galilei used a telescope in 1610 and spotted what we now know as Saturn's ring system (although Christian Huygens was the first to identify them as actual rings). The planet has nine rings and three arcs, with two different divisions. They might have originated with some of the nebulous material left over from Saturn's formation, or the rings could have come from a moon that got too close to the planet and disintegrated. Most researchers believe that the rings can't be as old as Saturn itself.

Some of the planet's 62 moons have serious impacts on the rings, either contributing to the matter within them or helping to shape them with their own gravitational pulls. Most of Saturn's moons are so tiny that they're less than ten kilometres (6.2 miles)

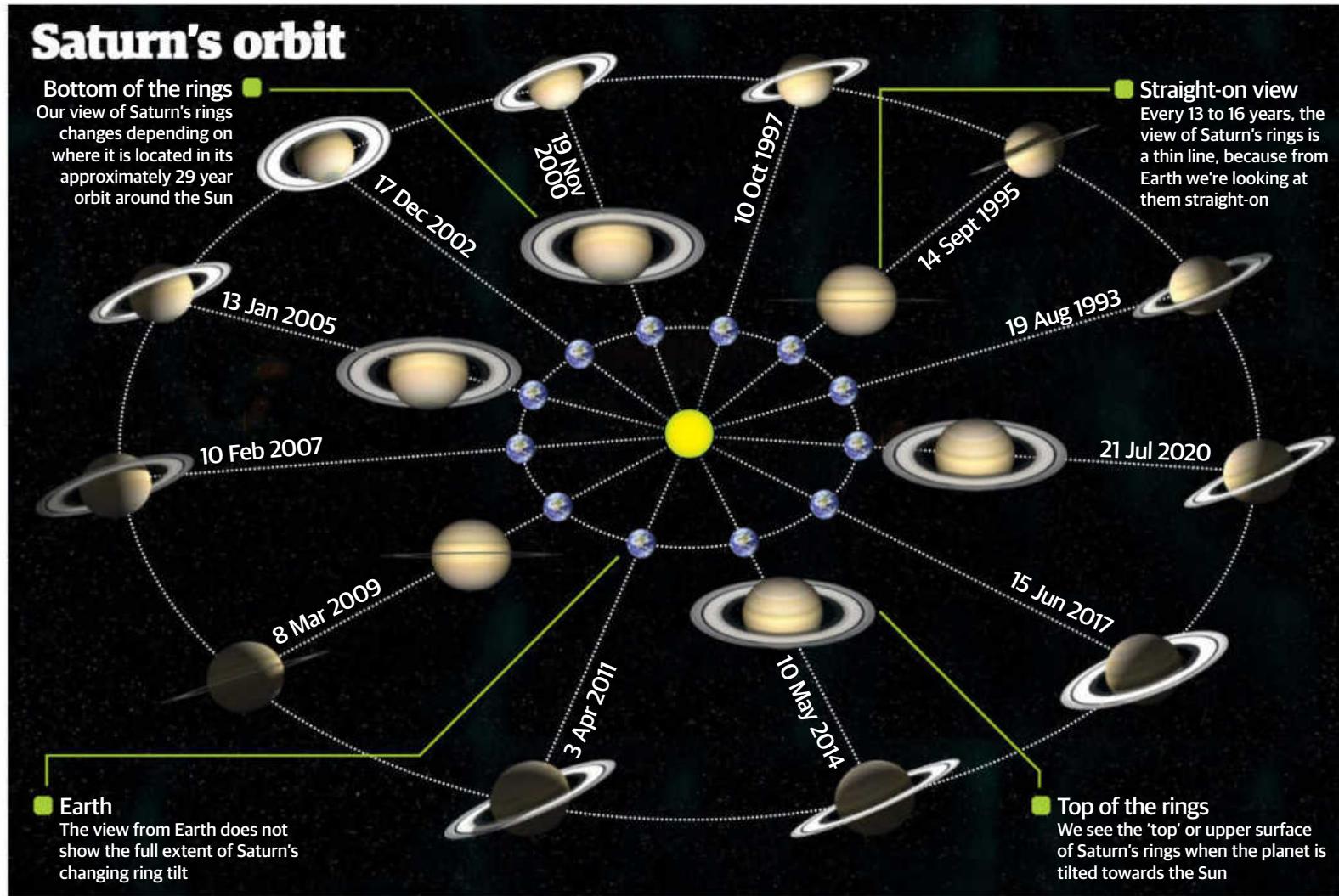
in diameter, but some of them are unique in the Solar System. Titan, for example, is the biggest, comprising approximately 90 per cent of the mass around the planet and is larger than Mercury. It's also the only known moon to actually sport an atmosphere, while Saturn's moon Rhea might even have rings of its own.

On average, Saturn is 1.4 billion kilometres (890 million miles) away from the Sun. It receives approximately one per cent of the sunlight that we get here on Earth. Saturn has an extremely slow orbit, taking around 29.5 years to complete one. This means that although the planet's tilt gives it seasons during the rotation, each of these seasons are a little more than seven years long. Because of

the rings, the seasons give us very different views of the planet from Earth - they might tilt 'up', 'down', or on the same plane as Earth depending on where Saturn is located in its orbit (which means that they can seem to disappear unless you're using a very powerful telescope).

But how long is a day on Saturn? We aren't entirely sure. The haze and clouds keep us from being able to directly view the surface of the planet using telescopes or probes, and we know that the clouds generally orbit at a constant speed so we can't use variations to make that determination. In 1980, the Voyager 1 space probe took readings of radio emissions from the planet to measure the rotation of the planet's magnetic field, and gave

**"Saturn is more than 95 times more massive than the Earth, although it has just one-eighth the density"**



an estimate of ten hours, 39 minutes, and 22 seconds. Then, in 2004, the Cassini spacecraft returned an estimate of ten hours, 45 minutes, and 45 seconds.

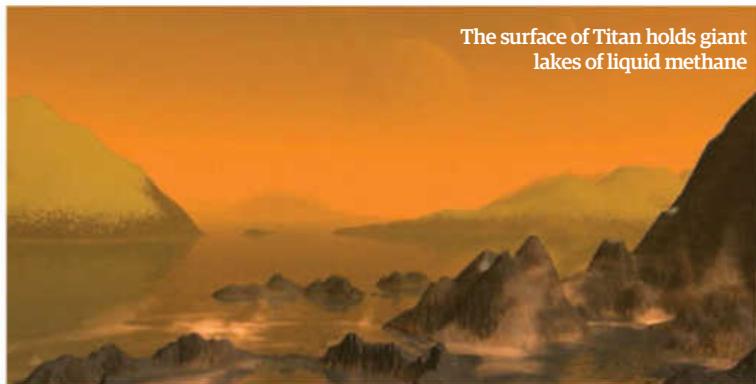
While six minutes may not sound like a particularly big difference, it has left scientists puzzled as to whether Saturn is slowing down in its orbit, or whether something else, such as solar wind, is interfering with the emissions. It's most likely to be the latter, however, and the current estimate, which is ten hours, 32 minutes and 35 seconds is a composite made up of various readings.

Regardless, it's a speedy rotation - so fast, in fact, that Saturn looks like a squashed ball as it spins on its axis - and the planet is also approximately ten per cent wider along its equator because of this. ■

Saturn has a little more than 95 times the mass of Earth, while its radius is about nine times that of the Earth's radius



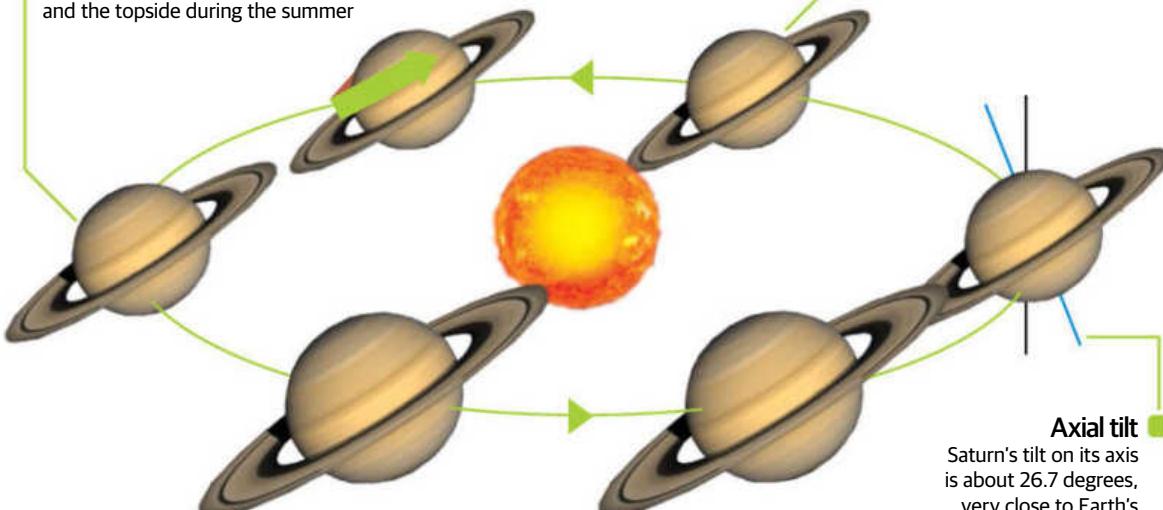
The surface of Titan holds giant lakes of liquid methane



## Seasons and tilt

### Solstices

Saturn has seasons like Earth, including winter and summer solstices (depending on which hemisphere is facing the Sun). But they last more than seven years. We see the underside of the rings during the winter and the topside during the summer



### Equinoxes

Equinoxes signal the beginning of autumn or spring depending on the hemisphere. The seasons and tilt mean that during equinoxes the rings seem to almost disappear from Earth because they're edge-on

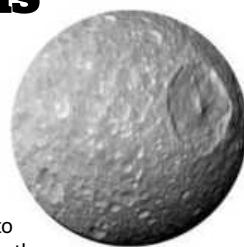
### Axial tilt

Saturn's tilt on its axis is about 26.7 degrees, very close to Earth's 23.5-degree tilt and rendered easy to see because of its rings

## The major moons

### Mimas

"That's no moon!" But in this case it is. Mimas is known for its appearance, which is similar to the *Star Wars* Death Star because of an extremely large impact crater (140km or 87 miles in diameter) in its northern hemisphere known as Herschel. It is a heavily cratered planet with a surface area that's about the same as Spain's.



### Enceladus

Enceladus is the sixth-largest moon of Saturn and is believed to have ice water under its frozen surface. The moon is unique because it's one of just three in the Solar System that has active eruptions - in this case, gigantic ice geysers that shoot out into space. This water ice contributes to the matter in Saturn's rings as well as falling as snow on the moon itself.



### Titan

The largest moon of Saturn is particularly interesting as it's the only moon in our Solar System known to have an actual atmosphere around it. While we could obviously never live on Saturn, some think that Titan is a viable option for colonisation in the future or even for extraterrestrial life. The moon also has liquids on its surface, a feature so far found only on Earth.



## The planets in relation to the Sun

Saturn lies 1.4 billion km (890 million mi) from the Sun on average, and 1.2 billion km (746 million mi) from Earth



**All figures** = million miles from Sun

### Saturn

Sixth planet from the Sun and second largest in Solar System

# Saturn inside and out

Saturn is often compared with Jupiter, but it can hold its own

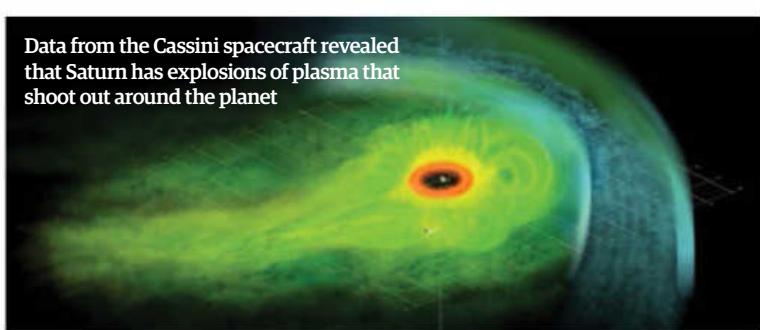
Saturn is one of the gas giants because it has no solid surface and it's mostly composed of gas. But it does have a rocky core, which is similar in composition to the Earth's. Comprising iron, nickel and silicate rock, it is estimated to be somewhere between 10 and 20 times the size of the Earth's core. Surrounding the core, there's a layer of ice made of ammonia and other elements, then a layer of highly pressurised metallic hydrogen, and finally molecular hydrogen that

changes from a liquid to a gas. The outer layers of the planet are different types of ice, including ammonia, ammonium hydrosulphide and water. The cloud cover is mostly coloured yellow by ammonia, and there's a mild weather system. Density, pressure and temperature all increase as you pass through the atmosphere and into the core, resulting in a very hot interior at about 11,700 degrees Celsius (21,000 degrees Fahrenheit). Saturn sends out more than twice as much energy as it

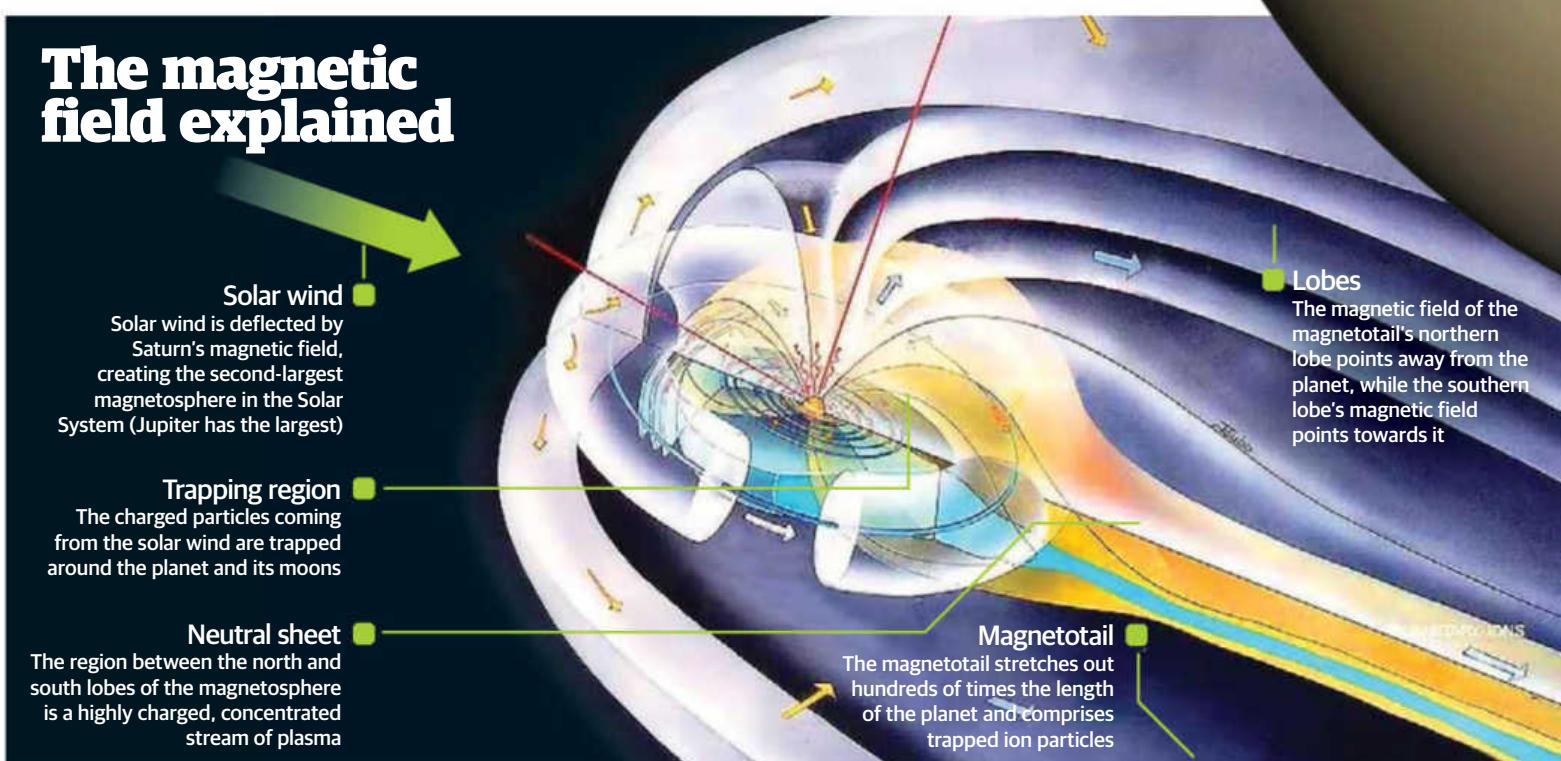
receives from the Sun. Some of this is due to gravitational compression, but we aren't sure if that can account for such a huge energy output. One possibility is an interaction between helium and hydrogen in the atmosphere, which may put out heat in the form of friction.

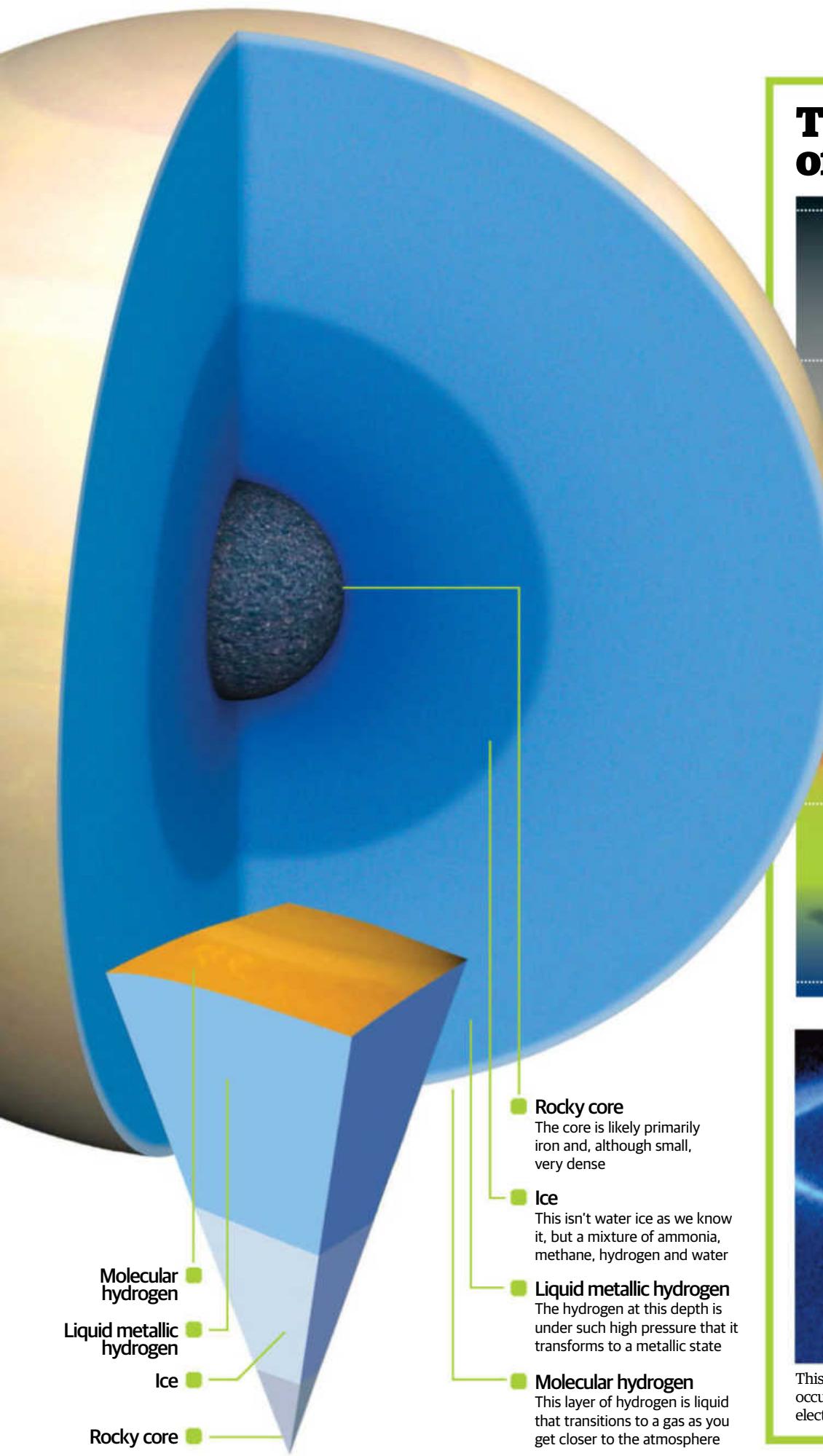
Saturn has a magnetic field 578 times stronger than Earth's. Scientists believe that the metallic hydrogen layer generates an electric current that is responsible for the magnetic field, called a metallic-hydrogen dynamo. The magnetic field is a dipole, with north and south poles. Aside from the rings, one of the most interesting features of Saturn is its auroras. These beautiful light displays have been captured at both the north and south pole regions by the Hubble Space Telescope and the Cassini probe, and appear as circles of light around each pole. ■

Data from the Cassini spacecraft revealed that Saturn has explosions of plasma that shoot out around the planet

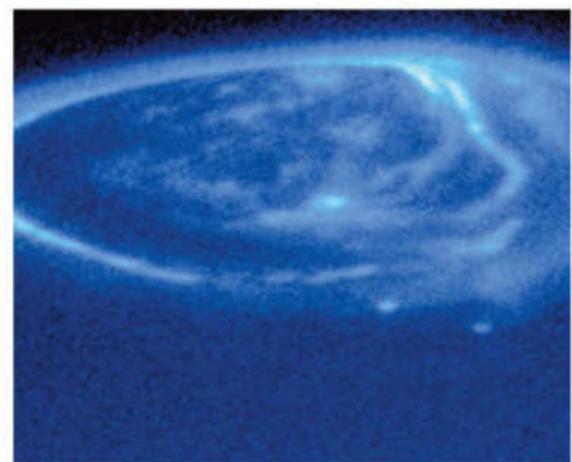
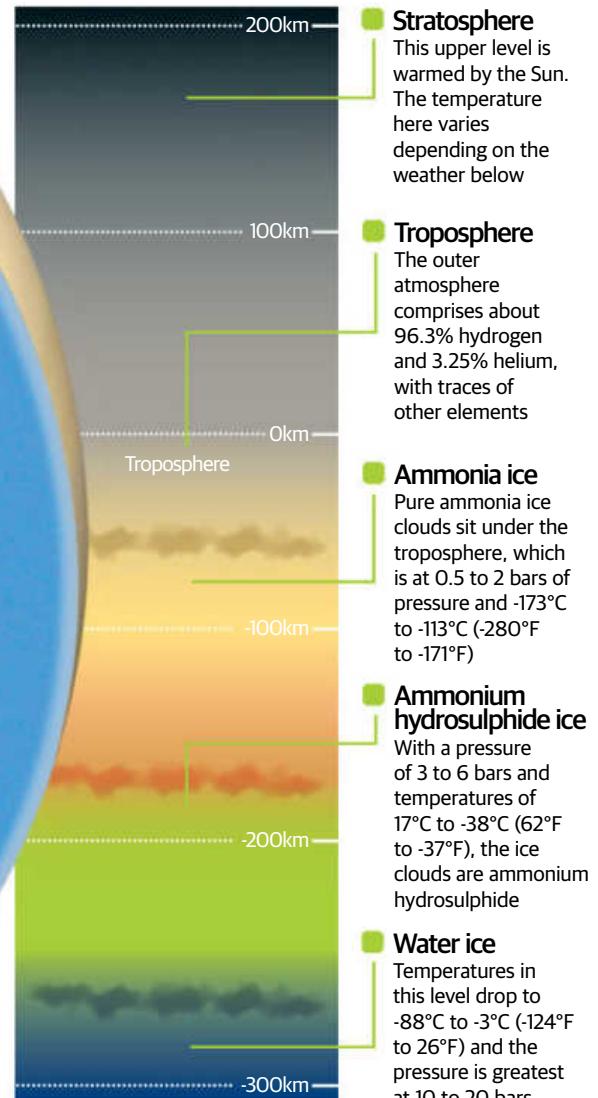


## The magnetic field explained





## The atmosphere of a gas giant



This image shows one of Saturn's auroras – loops of light that occur when gases in the upper atmosphere are excited by electrons in the planet's magnetic field

# In the clouds

Saturn's atmosphere has some similarities to Jupiter's

The composition of Saturn's clouds depends on where you are in the atmosphere. The pressure increases and temperatures drop as you travel further down through the layers and towards the planet's core. At the upper cloud layer, the clouds are made up of ammonia ice, followed by water ice clouds with a layer of ammonium hydrosulphide ice mixed in, and then the bottom layer is ammonia mixed in water droplets.

Much like fellow gas giant Jupiter, Saturn has bands of clouds that are

divided into zones and belts. The zones are the lighter-coloured areas and the bands are darker, with the orange and reddish hues coming from sulphuric compounds. The darker clouds tend to be thinner and lower, while the lighter ones are denser and higher. The bands of clouds are named in the same way that Jupiter's are labelled, according to their locations in the northern or southern hemisphere of the planet. However, Saturn's cloud bands are very faint and more difficult to distinguish

from each other than Jupiter's. They also widen as they head towards the equator. We weren't able to clearly see the distinctions between some of the fainter bands until the Voyager probes flew by Saturn during the Eighties (although modern telescopes are able to see them).

Again, like Jupiter, Saturn has wind jets that alternate westwards and eastwards out from the equator. But Saturnian winds are fast. In fact, reaching maximum speeds of around 1,800 kilometres per hour (1,120 miles

per hour), they are the second fastest winds among the Solar System's planets after Neptune's.

Saturn also has some unusual qualities at each of its poles. The north polar vortex has a unique hexagon-shaped cloud pattern, with straight sides estimated to be about 13,800 kilometres (8,600 miles) long, and it appears to rotate at the same speed as the interior of the planet. Scientists are unsure why the clouds have formed this particular pattern. The south pole doesn't have the same

## Global picture of a gas giant

**Equatorial Zone**  
The view of this zone on  
Saturn is bisected by its  
ring system, and the zone is  
wider than on Jupiter

**Rings**  
The rings disappear into  
a thin line when Saturn is  
viewed straight-on

kind of cloud patterns, but it is much warmer than the rest of the planet and is believed to be the warmest spot on Saturn.

There isn't a particularly strong weather system on Saturn - it's generally very mild. However, there are the occasional storms that show up as white spots. In 1990, the Hubble Space Telescope managed to capture a massive storm near the planet's equator that was not present during the Voyager encounters. This was an example of what is known as a Great White Spot (named after Jupiter's Great Red Spot). This mass of clouds occurs every 30 years or so, or roughly once every Saturnian year. The Cassini mission also spotted a storm in 2006 near the planet's south pole, which looked a lot like a hurricane on Earth. ■



This infrared image from Cassini shows a close-up of the swirling clouds on Saturn's banded planetary surface

#### ■ Northernmost Temperate Belt

This belt is wavy due to an unusual, hexagonal-shaped polar vortex located at Saturn's north pole

#### ■ Storm

Although much milder than Jupiter, Saturn still has white spots occasionally, indicating storms occurring in the clouds

**“The north polar vortex has a unique hexagon-shaped cloud pattern, with straight sides estimated to be about 13,800km long”**

# The ring system

## The feature that makes the jewel of the Solar System shine

Although Saturn isn't the only planet in our Solar System with a system of rings, it's the only one with a system this big. There are billions of tiny particles, mostly ice but with some rocky material, too. Despite the fact that they increase Saturn's brightness, we weren't even aware of its ring system until Galileo observed them via telescope. He was confused a few years later when the rings seemed to disappear, not knowing that they just weren't visible with his telescope when the Earth is on the same plane as Saturn. By the 1800s we knew that the rings were just that - not moons, not a single disc, but many rings comprising tiny particles.

Saturn's ring system is divided into rings, arcs, divisions and gaps. The first seven rings to be discovered were designated with letters of the alphabet A through G, but they were named in order of discovery so from innermost to outermost ring they are D, C, B, A, F, G and E. Three other named rings have been discovered since Ring G, but these are named after the moons that orbit with them: Janus, Epimetheus, Pallene and Phoebe. In addition to the rings, there are two ring arcs, incomplete trails of dust ejected by the moons Methone and Anthe kept in arc formation via resonance with two other gaps. There are also two divisions - the Cassini Division, between Rings A and B, and the Roche Division, a space between Rings A and F.

### A Ring

This ring is the outermost of Saturn's large, bright rings. It has a width of 14,600km (9,000 mi). There are two gaps within it as well as numerous tiny moonlets.

### B Ring

B Ring is the brightest and most massive ring and has a width of 25,500km (15,800 mi). While it doesn't contain any gaps, it does have a wide variety of materials that result in ringlets both bright and dark.

### C Ring

This ring is mostly transparent and faint despite its width of 17,500km (10,800 mi). It has two gaps with each containing a ringlet.

### D Ring

The D Ring is the innermost ring and only 7,500km (4,600 mi) wide. It's also very faint and difficult to see.

### E Ring

Saturn's outermost ring, the E Ring, contains smaller ice particles than all the others. It is 300,000km (186,000 mi) wide.

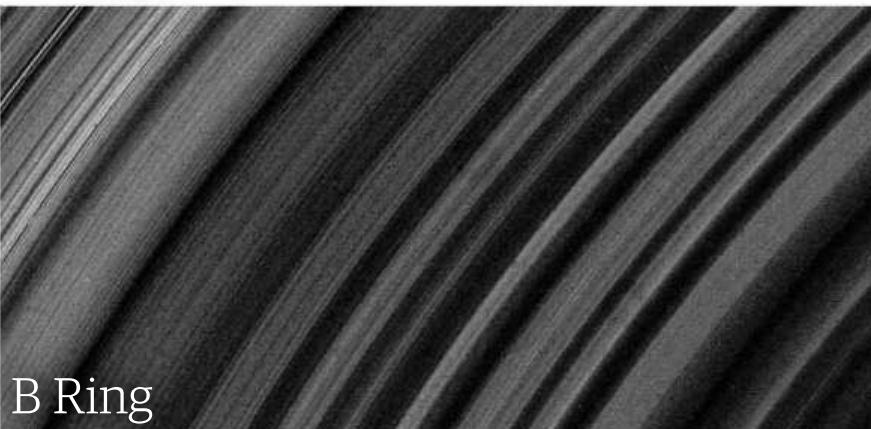
### F Ring

This ring is known as the most active of Saturn's ring system. It has one core ring with a spiral ring coiling around it that is strongly affected by the orbit of the moon Prometheus.

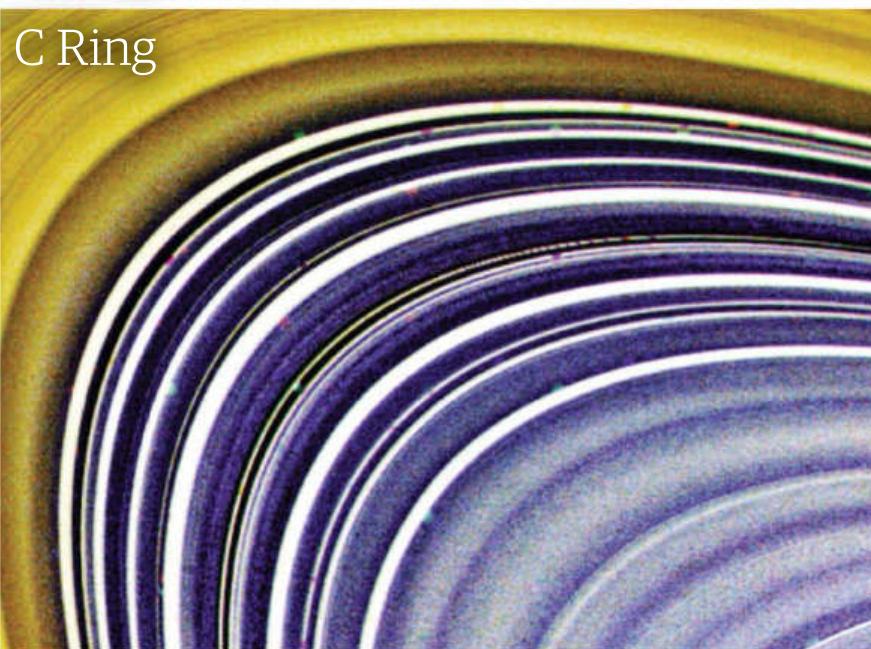
### G Ring

The G Ring is halfway between rings F and E, with a very bright inner edge that contains a moonlet called Aegaeon, which is probably the source of the ring's ice particles.

A Ring



B Ring



C Ring



D Ring

C Ring

B Ring



Colombo Gap

This gap, in the inner C Ring, contains a ringlet of its own called the Titan Ringlet (named because it is in orbital resonance with the moon Titan)



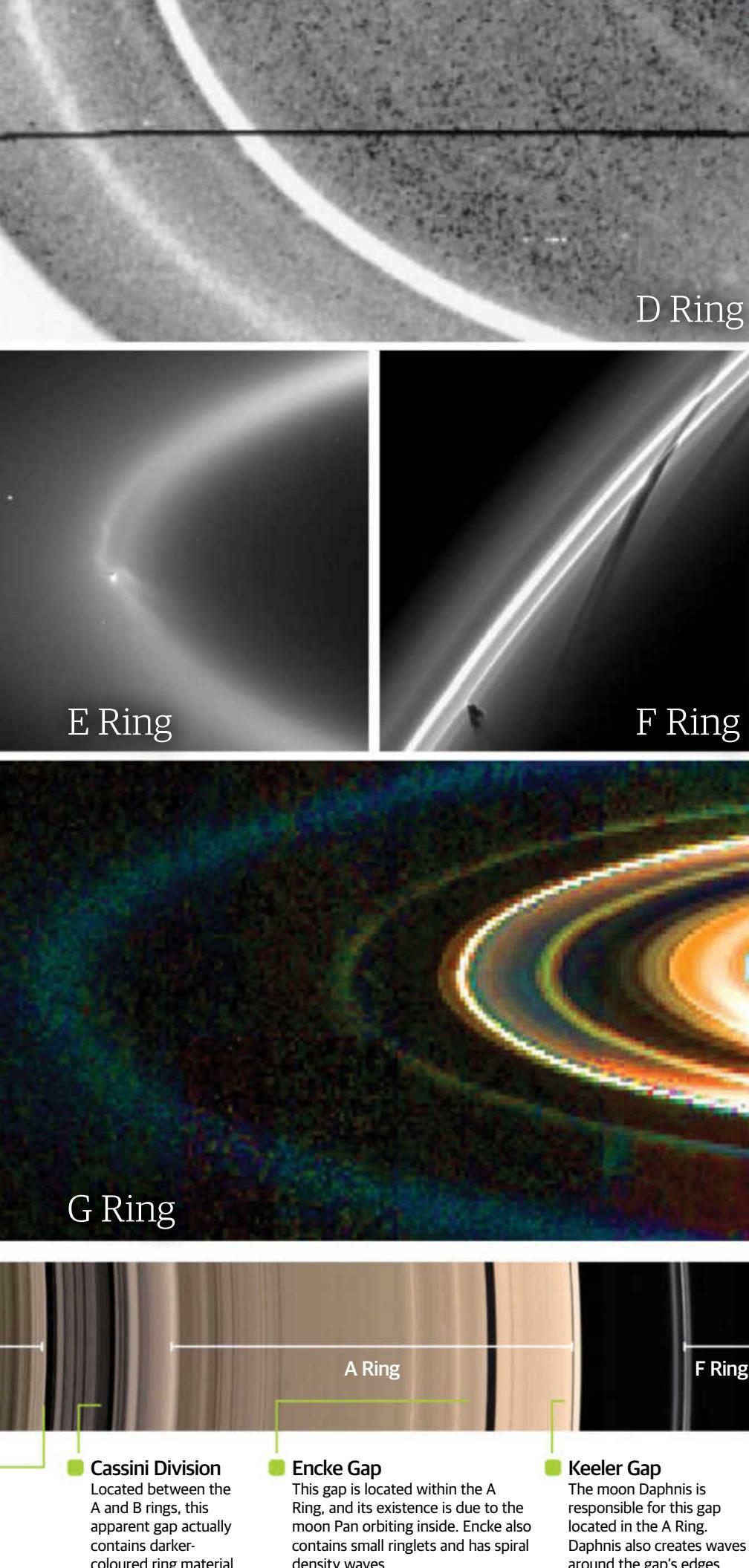
Maxwell Gap

Situated within the outer C Ring, the Maxwell Gap also has a ringlet, but it's not circular and contains wavy structures



Huygens Gap

Found at the inner edge of the Cassini Division, this gap contains a dense ringlet with an unusual structure caused by resonance with the moon Mimas



## Saturn in numbers

Fantastic figures and surprising statistics about the ringed planet

**578 times**

Saturn's magnetic field is 578 times more powerful than Earth's

**92%** **14 years**

Saturn and Jupiter together comprise about 92 per cent of the planetary mass of the Solar System

Saturn's rings seem to disappear about every 14 years or so due to the fact they're so thin and we see them edge-on

**80.00kg**

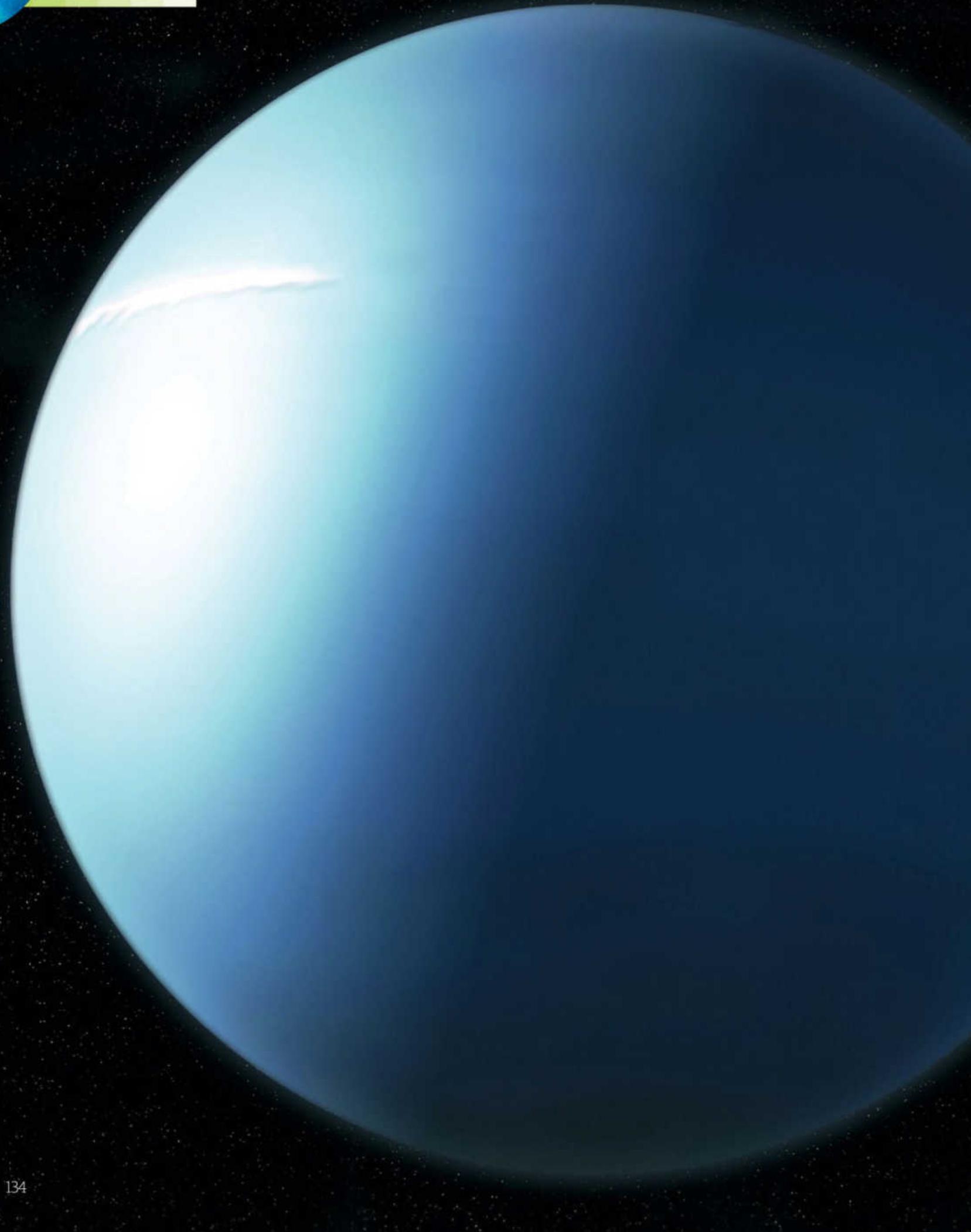
A person weighing 80.00kg (176.37lb) on Earth would weigh 85.10kg (187.61lb) on Saturn

**75%  $\frac{1}{8}$ th**

If the Earth had rings that spanned as wide as Saturn's, the rings would be 75 per cent of the way to the Moon

Saturn is twice as far away from the Sun as Jupiter is

**X2**



# All About... URANUS

The Solar System's forgotten planet has long been thought of as a dark, cold, characterless world, but the seventh planet from the Sun has its own unique twist and some fascinating features

While William Herschel officially discovered Uranus in 1781, he wasn't the first to observe it. Others thought it was a star and Herschel himself called it a 'comet' before deciding that it was, in fact, a planet - and the first one discovered by telescope. Although Uranus can be seen from Earth with the naked eye, it's so dim and has such a slow orbit compared to the other known planets that it didn't register as one. It just looks like a faint pinpoint of greenish or bluish light.

Uranus's acceptance as a new planet overturned beliefs that had been held for millennia about the size of our Solar System, and kicked off a flurry of planetary discovery. But despite Uranus's significance, we haven't spent much time visiting the planet. A flyby by Voyager 2 in 1986 marks the only time we've explored it. Because of this, we simply don't know a great deal about Uranus. Until telescope observations in the past few decades, we thought of it as a rather bland

planet: dark, cold, slow and with few interesting features.

Uranus is the third-largest planet by radius and the fourth-largest by mass. It's about 3 billion kilometres (1.86 billion miles) from the Sun, which means that it receives 0.0025 per cent of the sunlight that the Earth gets. Uranus is a gas giant, along with Jupiter, Saturn and Neptune, with the latter planet sometimes being referred to as its twin. It is the least massive of the four, but still more than 14 times more massive than Earth. Uranus has a diameter four times that of Earth's. It also has the coldest atmosphere of any other planet in the Solar System, with a mean temperature of approximately -197 degrees Celsius (-322 degrees Fahrenheit). Uranus also has a multilayered cloud system, although without the flashy variations of colour seen on planets such as Jupiter and Saturn. However, it does have a lot in common with the other gas giants. It has a magnetosphere that is very

similar to Jupiter's. It has 27 moons, and a system of 13 rings that was discovered not long after Saturn's ring system. It's most like Neptune in terms of composition, mostly hydrogen and helium with icy volatiles. Sometimes Uranus and Neptune are referred to as the 'ice giants'.

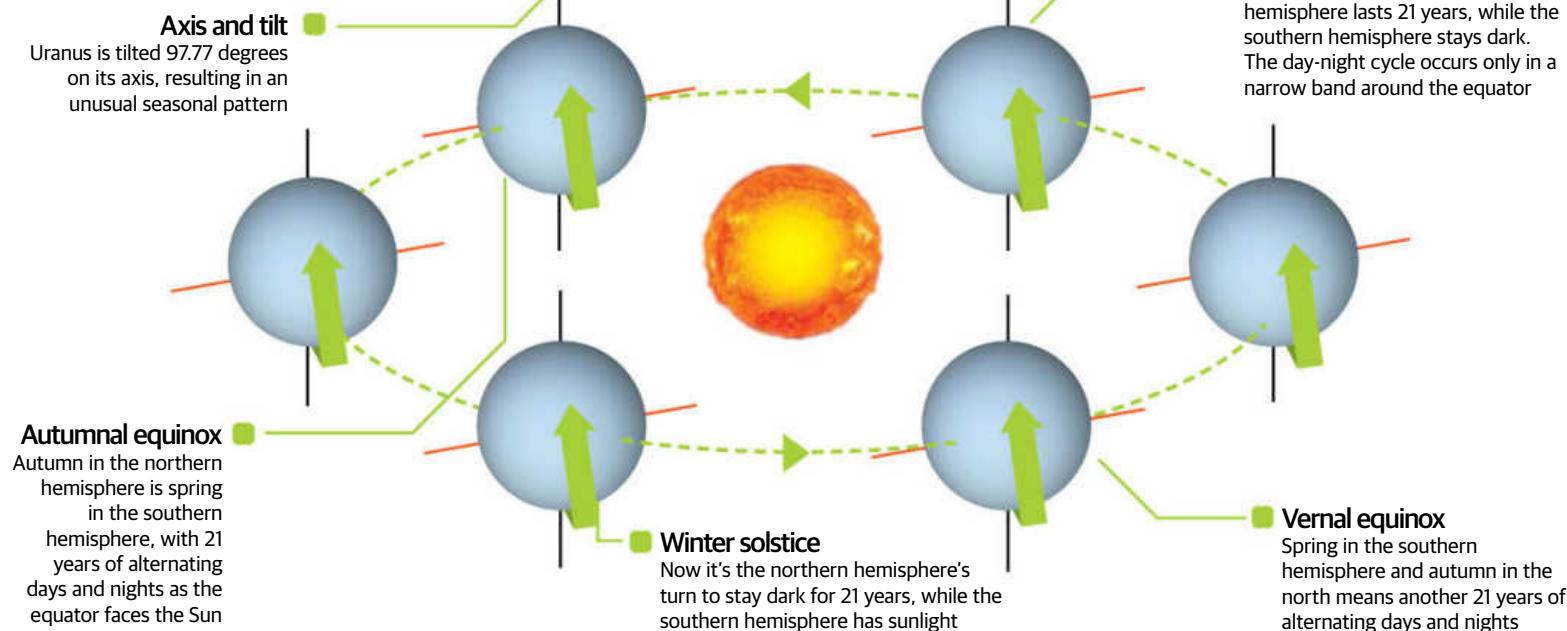
But Uranus can't just be lumped in with the other gas giants because the planet has its own unique twist. Literally, as Uranus's 97.77-degree axial tilt means that it is parallel with the plane of the Solar System - its poles are on either side. While other planets have extreme tilts, none are so perfectly perpendicular to the plane of its orbit. Recent studies show that Uranus is probably tilted due to at least

two violent, massive collisions one after another, with objects larger than Earth. These impacts likely occurred early in the planet's life, even before its moons formed, and have made astronomers rethink how the other gas giants formed as well.

The tilt has impacted just about everything about Uranus. It has extreme seasons and weather fluctuations since each hemisphere experiences either full Sun or deep space. Its magnetosphere is tilted and asymmetric. The ring system is also on its 'side', and comes close to rivalling Saturn's in complexity. The moon system is less massive than any other gas giant's system. So, in many ways, Uranus is unique. ■

**"Uranus can't just be lumped in with the other gas giants as it has its own unique twist"**

## Seasons and tilt

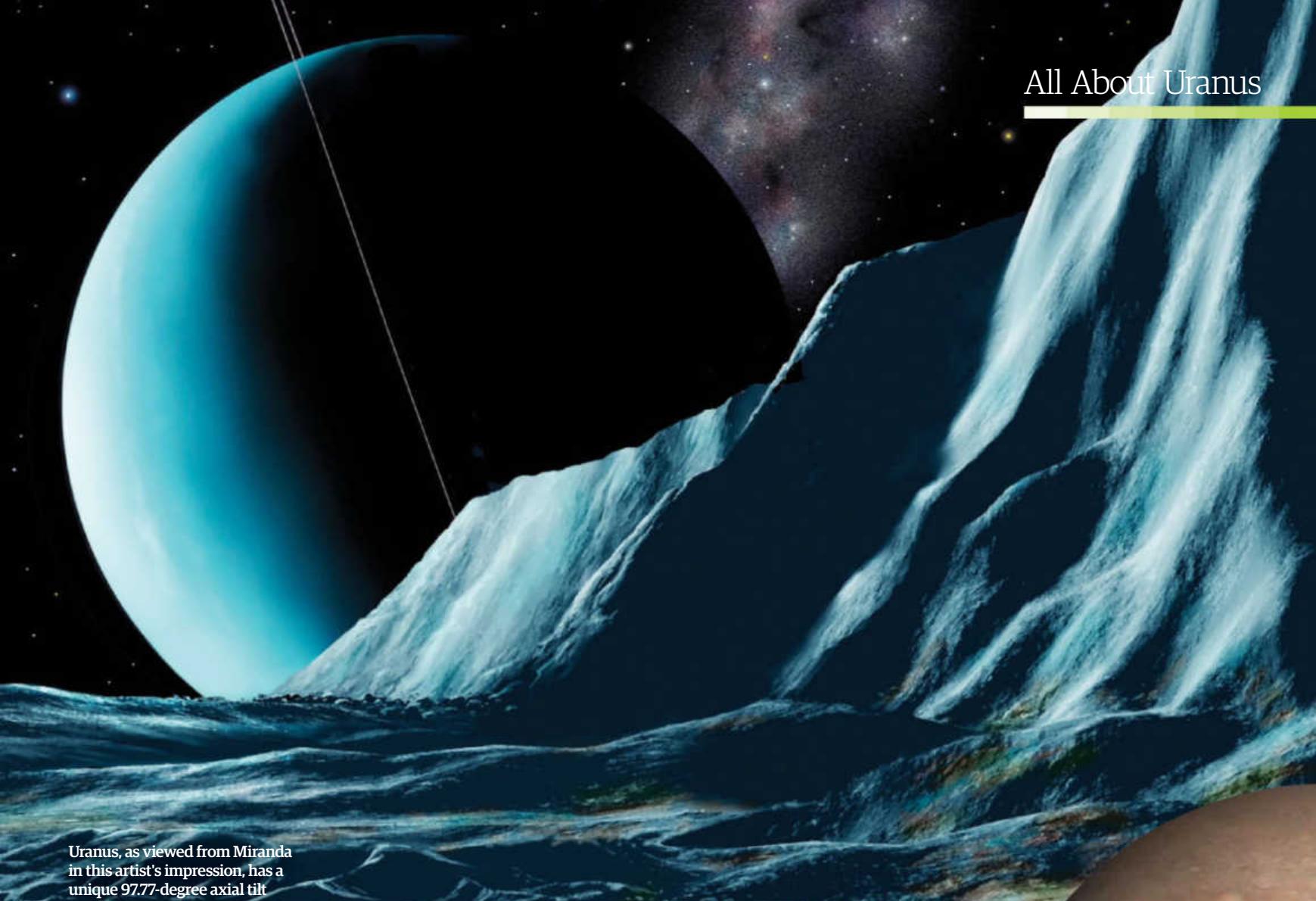


## The planets in relation to the Sun

Uranus lies 3 billion km (1.86 billion mi) from the Sun on average, and 2.57 billion km (1.6 billion mi) from Earth

All figures = million miles from Sun





Uranus, as viewed from Miranda in this artist's impression, has a unique 97.77-degree axial tilt

## A unique spin on a planet

### Geographic north pole

The huge difference between magnetic north and geographic north may be attributable to a very salty ocean beneath the planet's surface that is not located at its core

### Spin axis

Uranus spins on its side, and has been described as rotating like a beach ball

### Magnetic field

This varies greatly depending on the area. In the northern hemisphere it might be much stronger than Earth's; in places in the south, it's much weaker

### Magnetic north pole

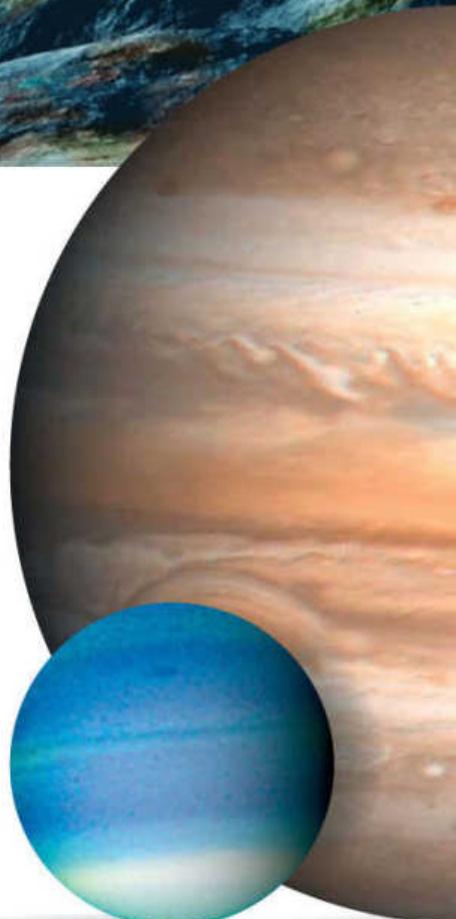
Uranus's magnetic north pole is a full 59 degrees tilted away from its geographic north pole

S

N

### Dipole field axis

The main magnetic field does not pass entirely through the planet, resulting in multiple poles



Compared to Saturn and Jupiter, Uranus and Neptune are very small gas giants. But Uranus is still more than 60 times greater in volume, 14 times greater in mass and four times greater in diameter than Earth

# Uranus inside and out

It has a very similar structure to Neptune but this ice giant still retains its mysteries

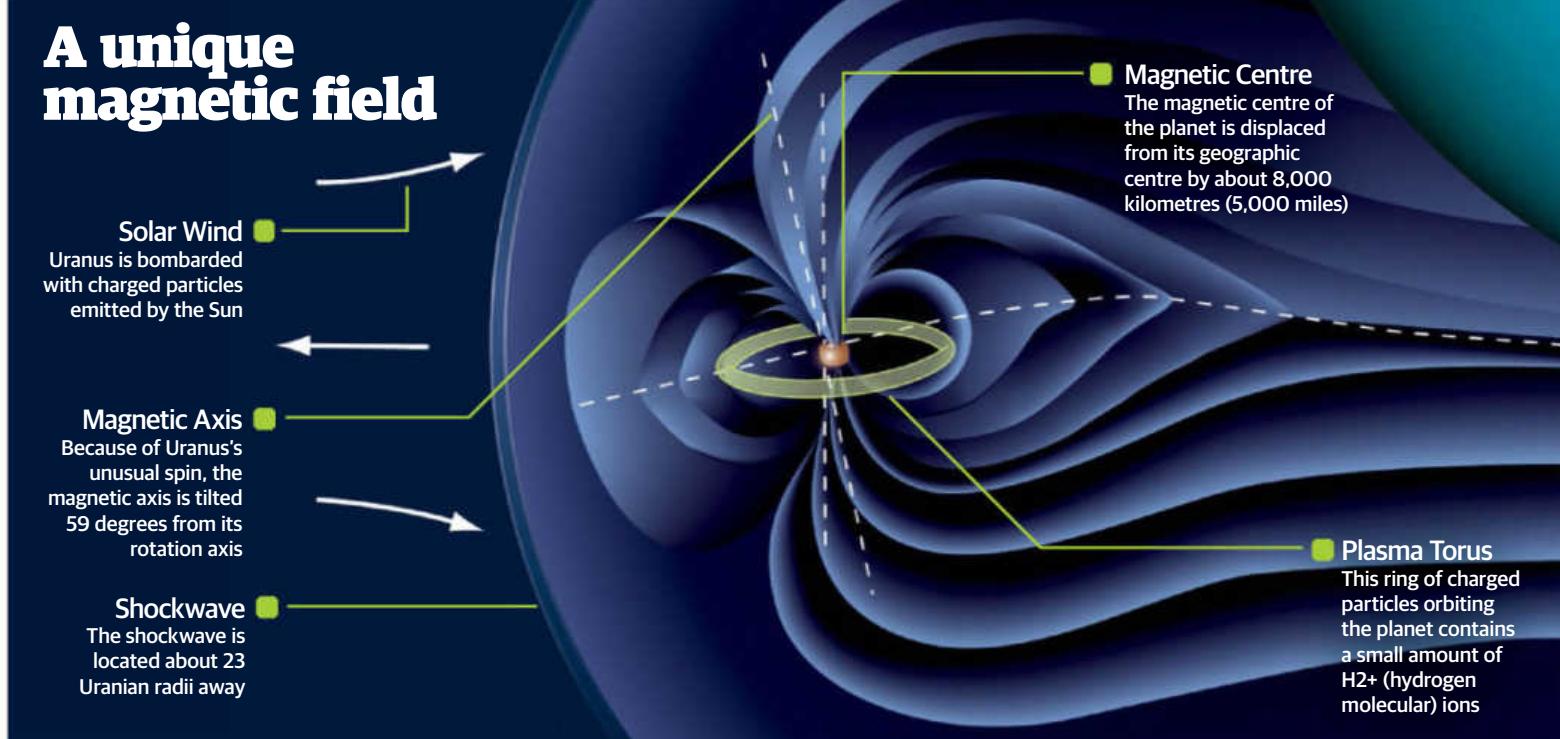
The term 'gas giant' implies that Uranus is solely composed of gases, but studies indicate that it actually has a core of silicate rock, encased in ices and topped with a gaseous layer. The core must be very small, since Uranus is the second-least dense planet. It likely takes up only 20 per cent of the planet's radius. The ice mantle surrounding the core is fluid, with volatiles like methane, ammonia and water. In fact, this electrically conductive fluid is often called an ammonia-water ocean. The outer layer is mostly helium and hydrogen.

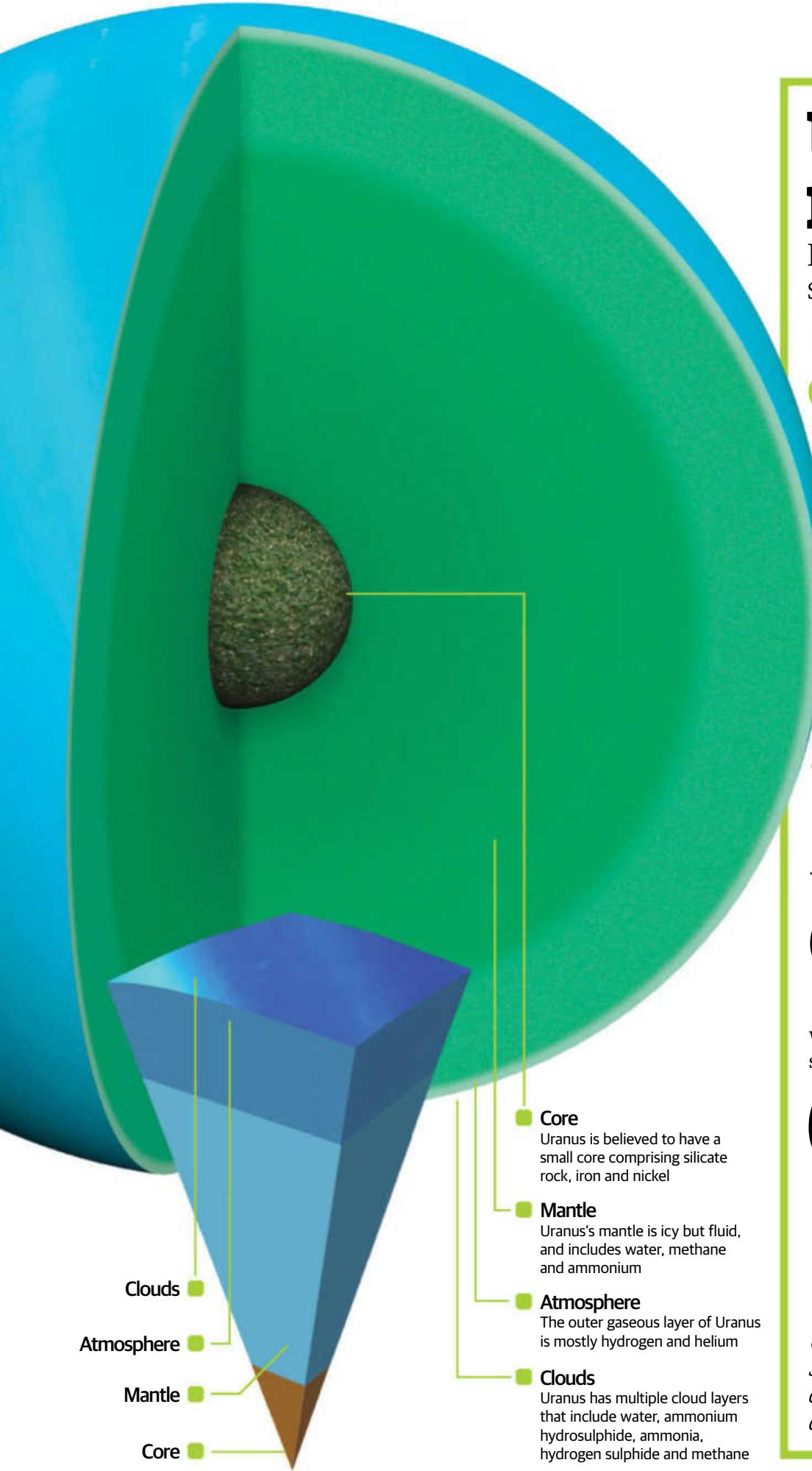
Uranus is also much cooler inside than the other gas giants - it's actually the coldest planet in the Solar System. Neptune radiates 2.61 times the heat that Uranus does. We aren't sure why Uranus is so cold in comparison, but it may have been struck by a large body that forced it to expel most of the heat

it had when formed, or there could be a complex system at work in the atmosphere that keeps core heat from getting out.

The atmosphere contains three layers: the thermosphere, the stratosphere and the troposphere. The lowest layer, the troposphere, is the most interesting and is rich in volatile ices like methane and ammonia. It has four cloud layers: methane, hydrogen sulphide and ammonia, ammonium hydrosulphide, and water clouds at the upper limit. We've only observed the top two layers, along with a hazy layer above them. The stratosphere sits between the troposphere and the outermost layer, the thermosphere. Uranus tends to look light bluish or greenish in colour, and it has faint darker bands. The overall colour is due to the way that methane absorbs visible and near-infrared light.

Until Voyager 2 explored Uranus's atmosphere, we didn't know much about its features. The probe found a bright polar cap at the south pole, as well as a lighter band called a collar. There were darker bands in the southern hemisphere and about ten lighter clouds around the middle latitudes. The timing of Voyager 2's arrival meant that it could not fully observe the northern hemisphere. In the Nineties, Hubble and ground-based telescopes like the Keck Observatory began to see more atmospheric features on Uranus. They spotted many more clouds in the northern hemisphere, which are brighter and at a higher elevation than the ones in the southern hemisphere. They also observed in 2007 that the southern collar had nearly disappeared, while one in the north had grown. ■





## Uranus in numbers

Fantastic figures and surprising statistics about the distant planet

**8.69m/s<sup>2</sup>**

The acceleration due to gravity on Uranus, compared to 9.8m/s<sup>2</sup> on Earth

**84 years**

*It takes Uranus 84 years to complete its orbit around the Sun*

**40kg**

*What you would weigh on Uranus if you weigh 45kg (100lb) on Earth*

**years**

The number of years it took Voyager 2 to reach Uranus after launching from Earth. Voyager 2 is still going strong after 35 years

**900km/h**

Wind speeds on Uranus can reach 250 metres per second (900km/h, 560mph)

**60X**

Uranus's volume is more than 60 times that of Earth

**-197°C**

*Uranus is the coldest planet in the Solar System, with an average temperature of around -197°C (-322°F). It can get as low as -224°C (-497°C)*

# Moons and rings

Uranus has 13 rings and 27 moons, but we could continue to find more

Discovering the Uranian ring system was a real surprise for astronomers. Since the planet is on its side, we have the opportunity to view the rings in a completely different way than we have for the rings of Jupiter and Saturn. Most of the rings were identified in 1977, with Voyager 2 and later the Hubble Telescope bringing the total to its current number of 13. Many of these rings are not quite in the plane of Uranus's equator, and most of them are not exactly circular. Unlike the rings of Jupiter, most of Uranus's rings comprise mostly microscopic particles of water ice and an unknown material - not dust. And in comparison to Saturn's rings, Uranus's rings are very dark. The brightness seems to vary depending on the angle of the ring.

Usually the Uranian rings are classified into three different groups. The nine main ones are very narrow - 6, 5, 4, Alpha, Beta, Eta, Gamma, Delta and Epsilon. The two dustier rings are in their own group: Zeta (1986U2R) and Lambda. The two outer rings are Nu and Mu. The brightest and

densest ring of the whole system is Epsilon. It is also the most eccentric, with a thickness that varies from 19.7 kilometres (12 miles) to 96.4 kilometres (59 miles). All of the rings seem to be very young in comparison to the planet. This means that they must be replenished by things like collisions of larger particles, moons or meteorites. The Epsilon ring has shepherd satellites - two moons, Cordelia and Ophelia - that confine it and define its inner and outer edges. But how do the rings without shepherd satellites maintain their shape and not spread out? This could mean that there are more moons we haven't seen.

All 27 of Uranus's moons are named after characters from the writings of either Alexander Pope or William Shakespeare. The first ones to be discovered were Titania and Oberon, seen by William Herschel in 1787. The most recent discoveries, such as Cupid and Francisco, were made using the Hubble Space Telescope in 2003. Despite their number, the moons aren't very massive - the mass

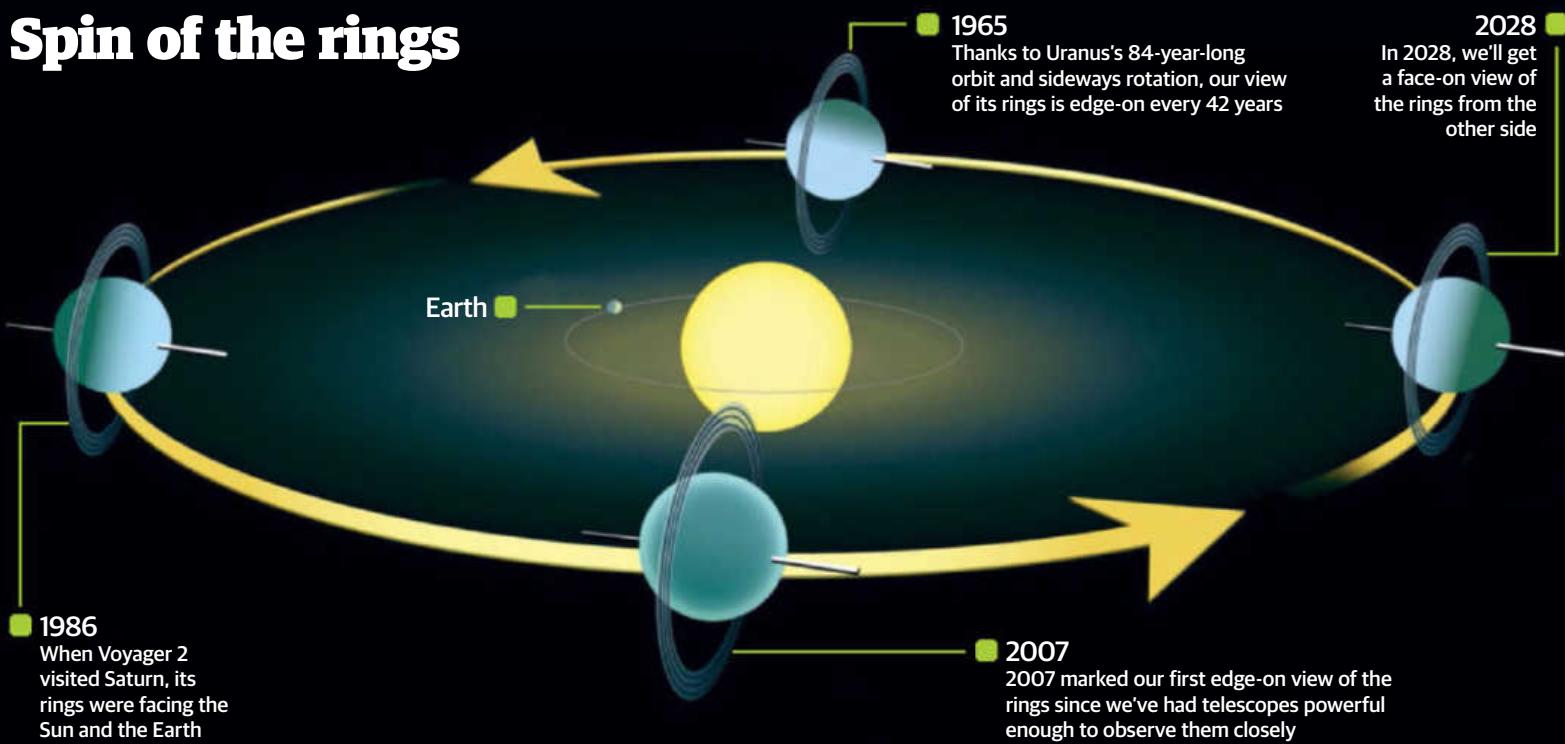
of the five major moons combined is less than half of the mass of Triton, Neptune's largest moon. These major moons are Miranda, Ariel, Umbriel, Titania and Oberon. The largest of these is Titania, with a radius of 789 kilometres (490 miles). All of the major moons have planetary mass and hydrostatic equilibrium - meaning that they have enough gravity to keep them spherical. If they were in orbit around the Sun instead of Uranus, they would probably be considered dwarf planets. Except for Miranda, which is primarily ice, the major moons seem to be equally rock and ice. The largest ones might even have differentiated interiors, with cores and mantles. They're mostly heavily cratered from impacts with meteors and other objects. And, except for Umbriel, they all show signs of geological activity.

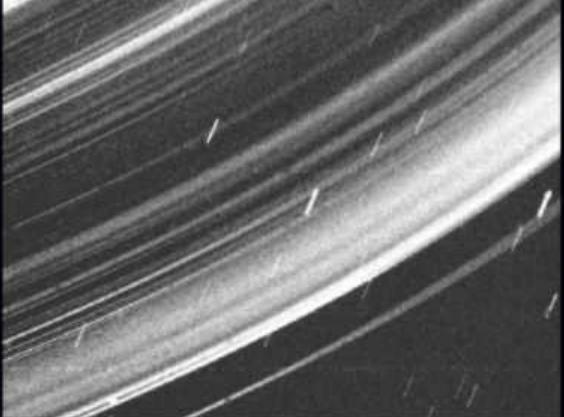
Inside Miranda's orbit lie 13 inner moons, each of which are associated with one of the rings. We know very little about most of these moons - only Puck was imaged by Voyager 2. It's the largest at 162 kilometres (100 miles) in diameter. These small moons are generally dark coloured and are highly perturbed by each other, with unstable orbits.

The nine irregular moons orbit very far away from Uranus compared to the other moons, and were probably captured by Uranus's gravitational pull soon after the planet formed. They have eccentric orbits and all but one, Margaret, are retrograde (meaning they orbit in the opposite direction of the planet). The largest at about 150 kilometres (93 miles) in diameter is Sycorax. There are likely to be even more irregular moons that we haven't yet discovered. ■

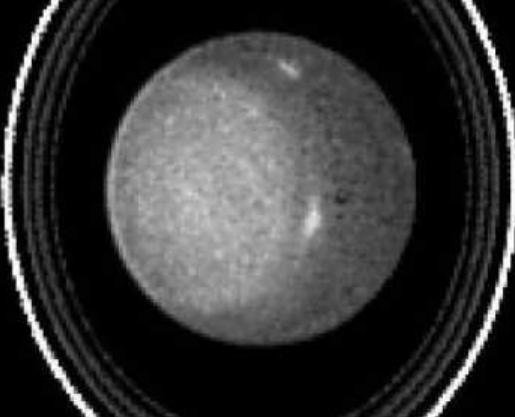
**"The mass of the five major moons combined is less than half of Triton's mass"**

## Spin of the rings





This image, taken by Voyager 2, shows the small dust particles distributed throughout Uranus's ring system



This 1994 image taken by Hubble provided the first view of the south pole haze and the ring system since Voyager 2



## The orbits of the moons

### 1. Miranda

The smallest and innermost of Uranus's five major moons, Miranda orbits the planet at around 129,390 kilometres (80,400 miles).

### 2. Mab

Although photographed by Voyager 2, Mab's existence was not confirmed until 2003. Its size is unconfirmed, but we know that it is highly perturbed by the orbits of neighbouring moons.

### 3. Puck

Puck is the largest inner moon of Uranus, and lies between the rings and Miranda, the first of the larger moons.

### 4. Cupid

Discovered in 2003, Cupid is the smallest of the inner moons at just 18 kilometres (11.2 miles) in diameter.

### 5. Portia

The second-largest inner moon, Portia heads a group of moons with similar orbits. It has a diameter of about 140 kilometres (87 miles).

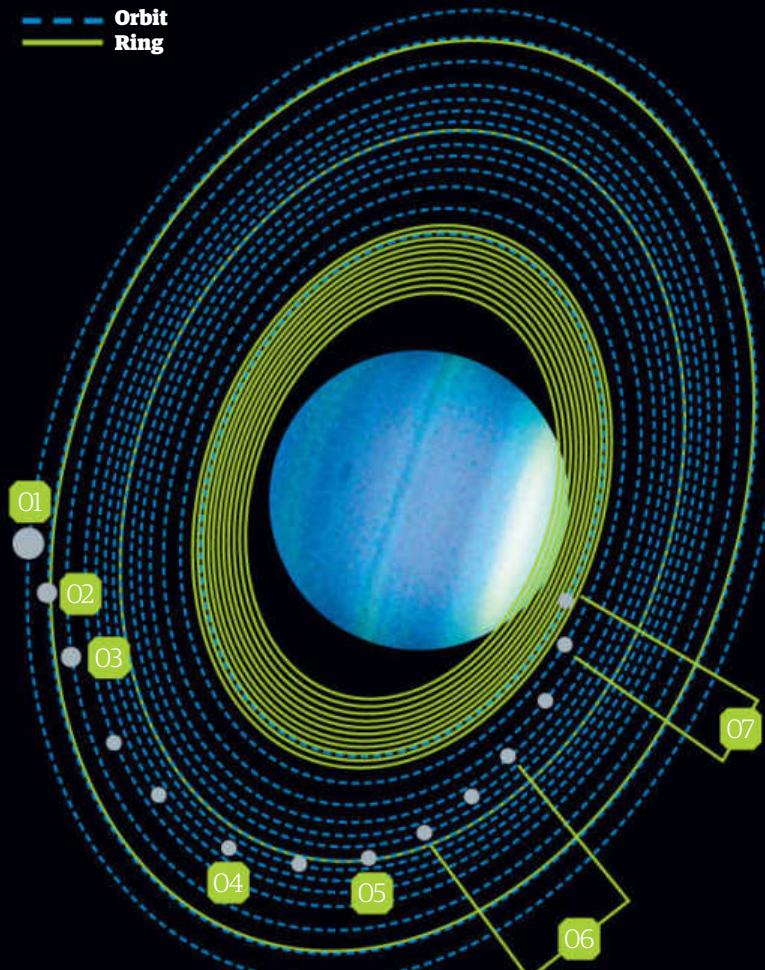
### 6. Juliet, Desdemona and Cressida

Little is known about these small neighbouring moons, but their chaotic orbits may result in collisions within 100 million years.

### 7. Ophelia and Cordelia

These innermost known moons serve as shepherd satellites – defining the inner and outer edges of Uranus's Epsilon ring.

Orbit  
Ring



## The major moons



### Miranda

The innermost and smallest of Uranus's five major moons has a diameter of just 472km (290 mi)



### Ariel

The fourth-largest moon, Ariel also has the third-greatest mass. Voyager 2 imaged about 35 per cent of its surface



### Umbriel

Umbriel has the darkest surface of the Uranian moons, and is one of the most heavily cratered



### Titania

Titania is the eighth-largest moon in the Solar System with a diameter of around 1,580km (980 mi)



### Oberon

Oberon is the outermost of the five major moons and is partially outside of Uranus's magnetosphere

## Discovering the rings

When William Herschel discovered Uranus, he also claimed to see a faint ring around the planet. It seems unlikely he was truly able to see anything, however. The ring system was officially discovered by a team working with the Kuiper Airborne Observatory (KAO). In 1977 and 1978, the team found a total of nine rings around Uranus. KAO was the first airborne astronomical research observatory, based at the NASA Ames Research Center in California. A military jet aircraft was modified to carry a 91.5cm (36in) reflecting telescope used to conduct infrared astronomy. Why a telescope on a plane? The aircraft was used to fly above 13,716m (45,000ft). This altitude is above the layer of water vapour in the Earth's atmosphere that absorbs infrared radiation, allowing the team to use the telescope to observe other planets in our Solar System.

Dr James Elliot, an astrophysicist with the KAO team, was an expert in stellar occultation – learning about a planet by measuring the light blocked when it passed between the Earth and a distant star. While working with data recording during an observation of Uranus, Dr Elliot noticed that the light between the planet and the distant star went dim for a few minutes before Uranus appeared. This was the first evidence of the rings, confirmed by Voyager 2 about a decade later.



# All About... NEPTUNE

A frozen world on the outermost limits of our Solar System, Neptune is a mysterious planet with its own unique characteristics



This image of the planet Neptune, seen as a small blue disc in the centre, was taken from the Earth in 1998 using a camera fitted to a telescope

Each planet is unique, and Neptune's claim to fame is being the first planet to be discovered not by observation, but by prediction. French astronomer Alexis Bouvard spent a lot of time closely observing the orbit of Uranus, and detected a gravitational perturbation that he deduced could only be explained by the existence of another planet. From his observations, other astronomers calculated the location of Neptune. To be fair, Galileo actually spotted Neptune more than 200 years before, but since he thought it was a star, he didn't get the credit.

There's still some debate over who did deserve the credit - French

astronomer Urbain Le Verrier or British astronomer John Couch Adams - and some sources include a third astronomer, Johann Galle of Germany. At any rate, Galle was the first to look at Neptune and understand what he was seeing, using calculations from Le Verrier, on 23 September 1846. He discovered Neptune's largest moon, Triton, shortly afterwards. Given the distance - 4.3 billion kilometres (2.7 billion miles) from Earth - Neptune is not visible to the naked eye. But if you use strong binoculars or a telescope, you'll see the planet as a small blue disc. Until powerful modern telescopes on the ground and the invention of

the Hubble Space Telescope, it was difficult to really study Neptune.

Neptune is the third-largest planet by mass, and 17 times the mass of Earth. It's also the fourth-largest planet by diameter. As the eighth planet from the Sun, Neptune was the furthest known planet until Pluto was discovered in 1930. Although it's back to being the outermost planet since Pluto's demotion, Neptune was still occasionally the outermost planet prior to that because Pluto's eccentric orbit caused it to cross inside Neptune's orbit on occasion. It's one of the four gas giants, and is also called Uranus's 'twin'. Because they're very similar in composition, both planets are often known as ice giants to distinguish them from Jupiter and Saturn. They're mostly made up of hydrogen and helium, with ices of water, methane, and ammonia, surrounding an icy

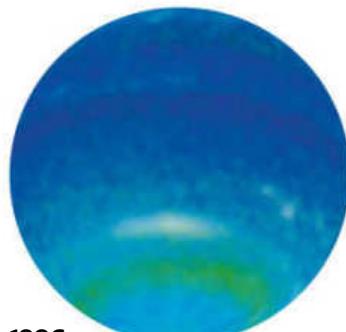
rock core. While the methane content results in Uranus having a blue-green colour, Neptune is a brighter blue. We're not sure what in the atmosphere intensifies the colour. Neptune also has an extremely cold atmosphere like Uranus, topping out at about -218 degrees Celsius (-360 degrees Fahrenheit) in the upper levels.

Although Neptune doesn't have the extreme horizontal tilt of Uranus, its magnetosphere is strongly tilted away from its rotational axis, at 47 degrees. Neptune also has a ring system and more than a dozen known moons. But that's where the similarities mostly end between the two planets. Uranus has a relatively dull atmosphere, for example, but there's lots happening weather-wise on Neptune. When Voyager 2 flew by in 1989 (the only spacecraft to visit Neptune), it observed lots of interesting weather. This includes some of the fastest winds in the Solar System, at around 2,000 kilometres per hour (1,240 miles per hour).

Neptune's tilt is much like Earth's at 28.32 degrees, so it has regular seasons, which happen to last about 40 years, because at 4.50 billion kilometres (2.8 billion miles) from the Sun, it has an orbit of 164.79 years. That means that in 2011, it completed its first orbit since it was discovered. Neptune's gravitational pull also has an impact on the Kuiper belt, a large ring of tiny, icy objects - including the dwarf planet, Pluto. Neptune's gravity has destabilised areas of the belt, and it has also created a resonance between the planet and at least 200 of the objects. ■

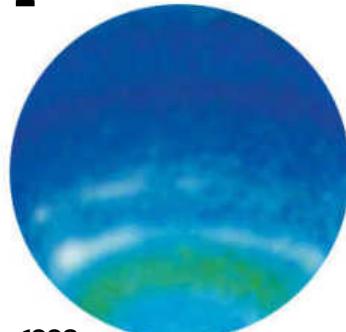
**"Neptune has some of the fastest winds in the Solar System, at around 2,000km/h"**

## Seasons on Neptune



**1996**

Neptune has four seasons in each hemisphere, just like Earth, but each one lasts about 40 years.



**1998**

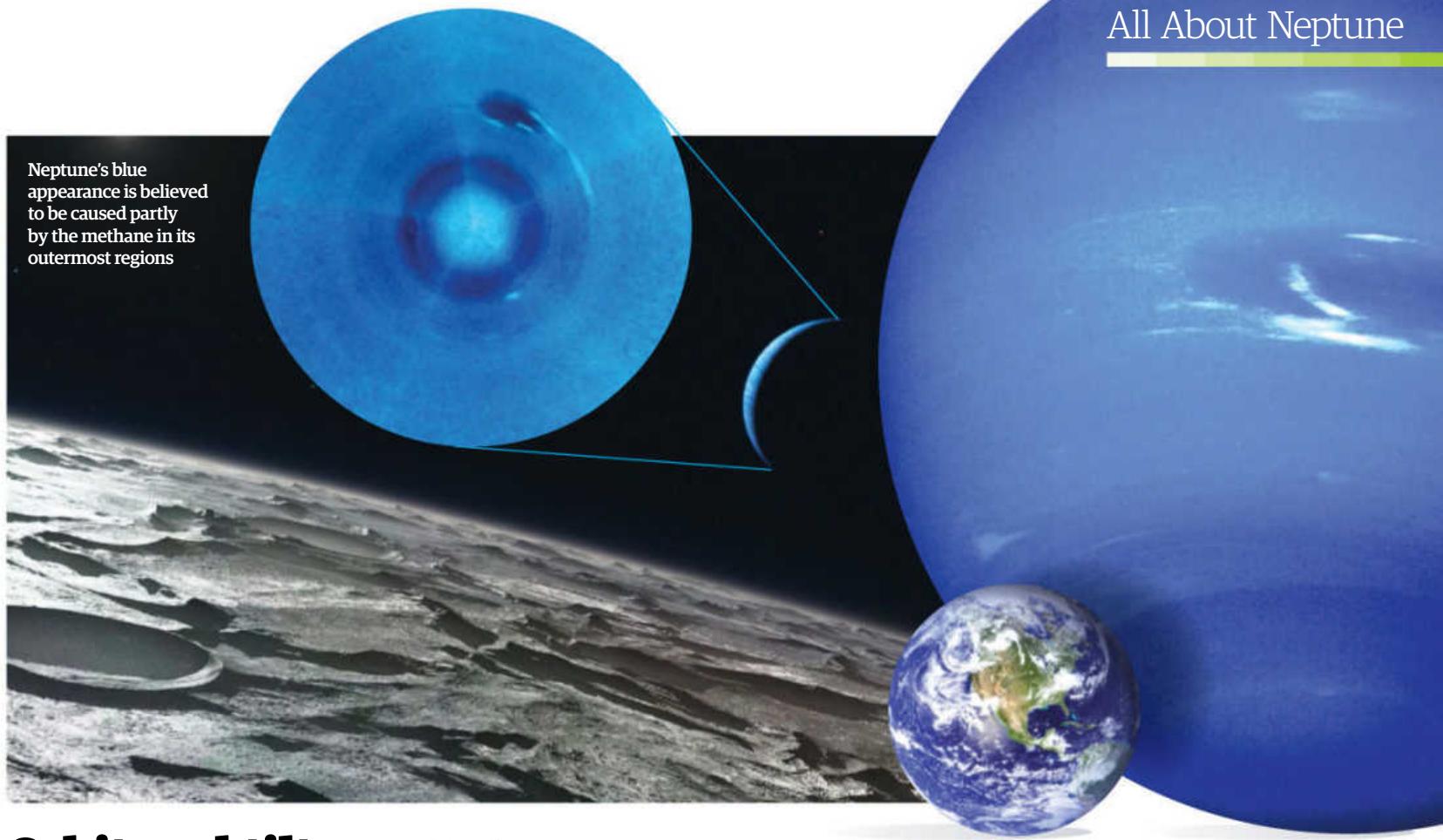
The cloud bands in the southern hemisphere brighten as spring begins on Neptune.



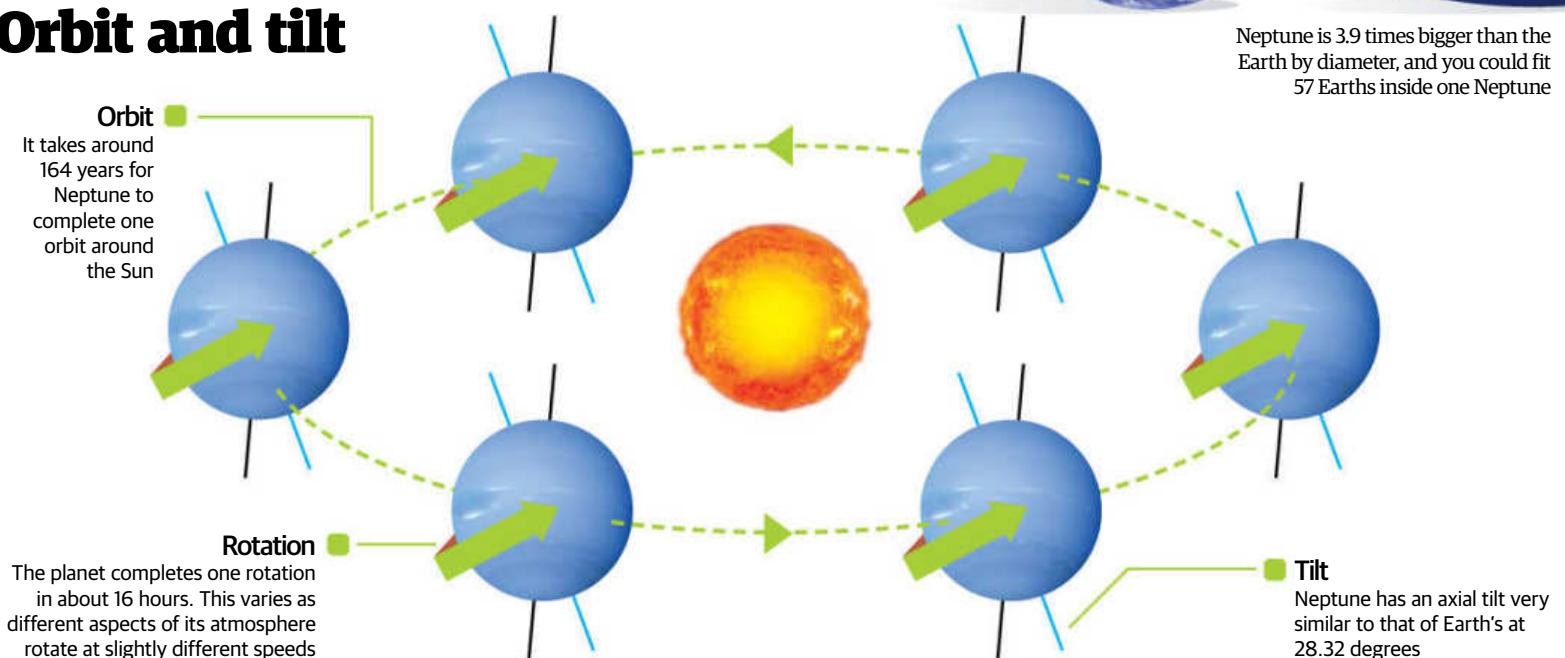
**2002**

There are about 20 more years of lightening clouds before the seasons change.

Neptune's blue appearance is believed to be caused partly by the methane in its outermost regions



## Orbit and tilt



## The planets in relation to the Sun

Neptune lies 4.50 billion km (2.8 billion mi) from the Sun and 4.3 billion km (2.7 billion mi) from Earth

All figures = million miles from Sun



# Neptune inside and out

Neptune is a lot like Uranus, but brighter blue, warmer and with more active weather

Like Uranus, Neptune is a gas giant but not solely comprising gases. Its core contains silicate rock, iron and nickel and is a little larger than planet Earth. Neptune's core is also under great pressure (twice as much pressure as the Earth's core) and about 5,100 degrees Celsius (9,200 degrees Fahrenheit). The mantle surrounding the core is icy, but that's a relative term when it comes to planet temperatures because it's actually a hot, dense liquid. Made of methane, ammonia, and water, the mantle is electrically conductive and its temperature ranges between 1,700 degrees Celsius (3,100 degrees Fahrenheit) and 4,700 degrees Celsius (8,500 degrees Fahrenheit). The mantle may also consist of additional layers, including a layer of ionised water (with electrically charged hydrogen and oxygen) and a deeper layer of superionised water.

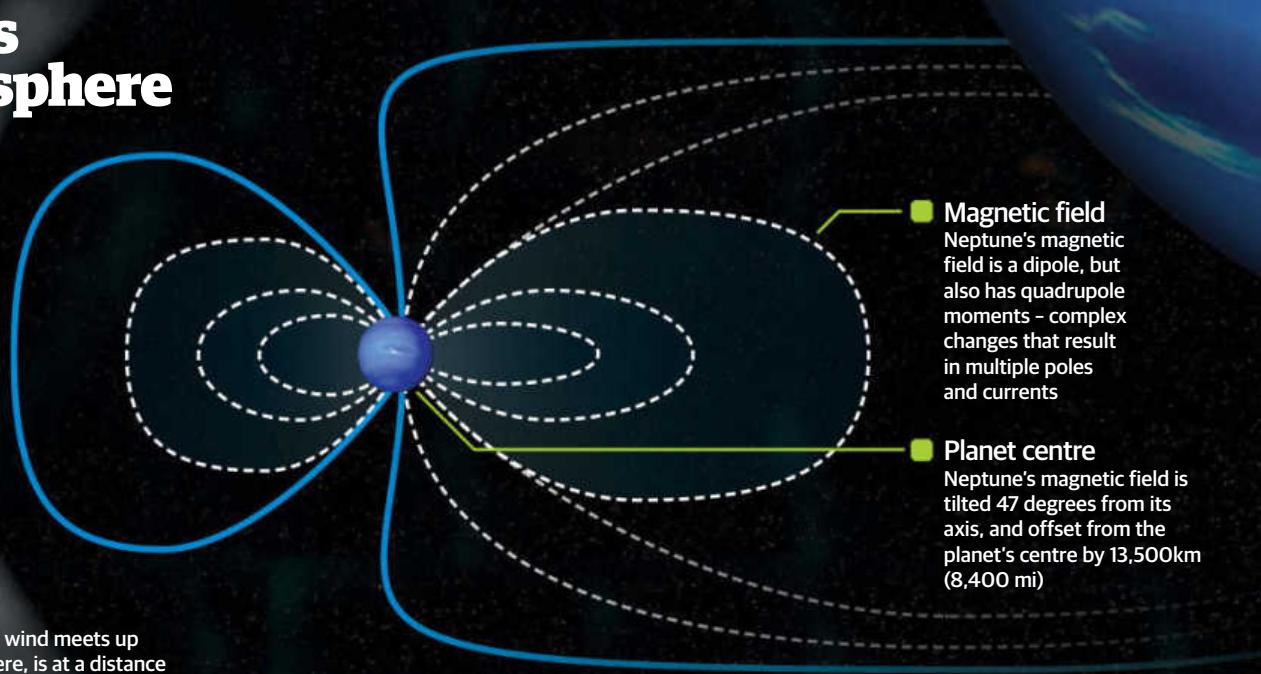
Neptune's atmosphere surrounding the mantle is about 80 per cent hydrogen, 19 per cent helium, and the rest traces of ammonia, water and methane. The methane, which absorbs red light in the spectrum, gives Neptune its colour. Since the atmospheric composition is supposed to be very similar to that of Uranus's, there must be something else in the atmosphere that makes Neptune a bright blue versus Uranus's bluish-green. It has two main divisions - the troposphere and the stratosphere. The troposphere probably has several different types of cloud bands, depending on where they're located. The lowest levels are clouds of hydrogen sulphide and ammonia. Then there are water ice clouds as the temperature drops, at a pressure of 50 bars. A cloud layer of water, hydrogen sulphide, ammonia and

ammonium sulphide floats above five bars of pressure. Between one and five bars, in the uppermost layer of the troposphere, the clouds are ammonia and hydrogen sulphide. Bands of these clouds wrap around the planet, casting shadows on opaque clouds below them.

Neptune is warmer overall than Uranus. Its stratosphere has traces of carbon monoxide, and the thermosphere is unusually warm at 480 degrees Celsius (900 degrees Fahrenheit) given Neptune's distance from the Sun. The planet radiates more than twice the energy of Uranus and receives only 40 per cent of the sunlight of its twin, yet has about the same surface temperature. We aren't sure why, but these differences in heat may be why Neptune has weather like storms and high winds, while Uranus does not. ■

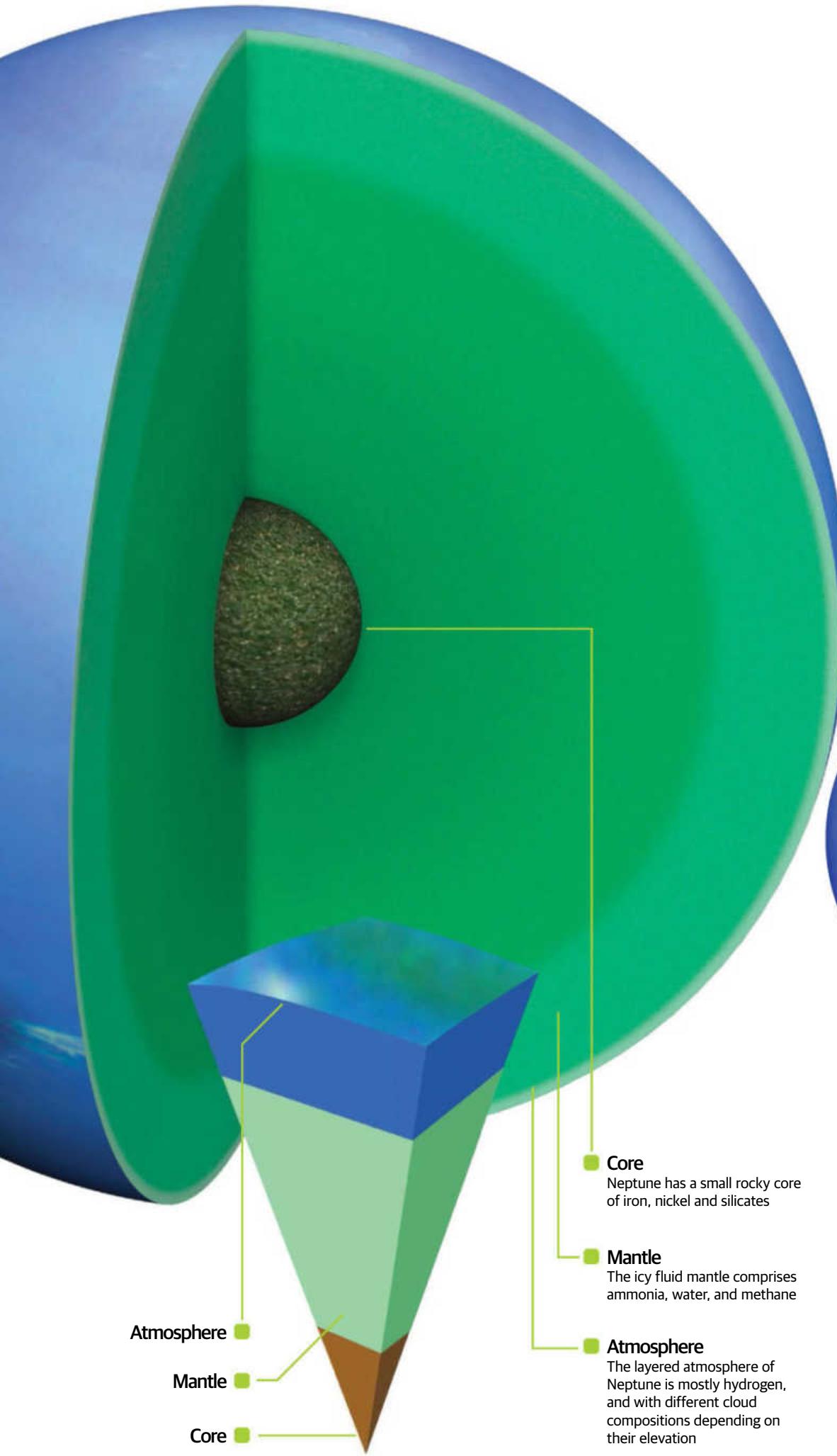


## Neptune's magnetosphere



### Magnetopause

The area where the solar wind meets up against the magnetosphere, is at a distance of 23 to 26 times the radius of the planet



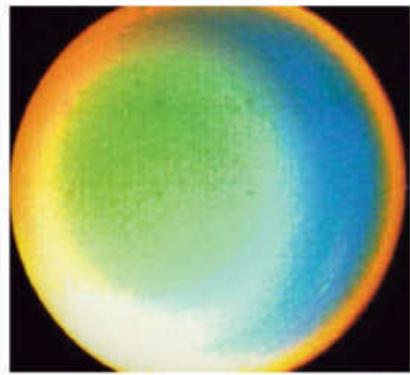
## Supersonic winds and storms

Neptune's massive winds and storms set it apart from Uranus. Most of the winds blow in retrograde rotation (opposite the planet's rotation), but the general pattern is prograde rotation (in the direction of the planet) in the higher latitudes and retrograde rotation in the lower latitudes. The winds reach almost 2,000 kilometres per hour (1,240 miles per hour) - nearly supersonic speeds.

On Voyager 2's flyby in 1989, it observed a massive anti-cyclonic storm that was 13,000 by 6,600 kilometres (8,700 by 4,100 miles) in size. The storm was dubbed the Great Dark Spot. It wasn't present when the Hubble Space Telescope viewed the planet five years later, but another storm was found and given the name. Neptune also has other large storms named the Scooter and the Small Dark Spot.



Neptune has storms, including hurricane-force winds that constantly blow around the planet



Special processing of this Neptune image taken by Voyager 2 shows the variations in temperature in its atmosphere

# Moons and rings

Neptune has two very different groups of moons - inner moons with regular, circular orbits, and outer moons with irregular, eccentric orbits

Neptune has 13 known moons. Triton is by far the largest moon, comprising more than 99 per cent of the total mass in orbit around the planet. It has a diameter of 2,705 kilometres (1,700 miles) and is the only spheroid moon. Triton was probably a dwarf planet in the Kuiper belt before being captured by Neptune's orbit. Astronomers believe it was captured instead of forming as a satellite because it has a retrograde orbit - it circles Neptune opposite of the planet's rotation. Triton has an irregular orbit, and is the second known moon (along with Saturn's moon Titan) to have an atmosphere. The atmosphere mostly comprises nitrogen, with some trace amounts of carbon monoxide and methane. It is also one of the coldest objects in the Solar System. The moon is very dense, and is probably two-thirds rock and one-third ice.

Triton is one of the seven outermost moons, which have irregular orbits. The next moon to be discovered, Nereid, was discovered in 1949. It is the third-largest moon. Unlike Triton, it has a prograde orbit. Nereid's orbit is also extremely eccentric - it gets as close as 1.4 million kilometres (850,000 miles) to

Neptune, but is 9.6 million kilometres (5.9 million miles) at its furthest point. The cause of its eccentricity is unknown, but it may have been perturbed by Triton, or have been a Kuiper belt object like Triton that was captured. We don't know exactly what Nereid looks like or what shape it takes. Two of the other irregular moons, Sao and Laomedea, have prograde orbits. Both were discovered in 2002. Halimede, Psamathe and Neso all have retrograde orbits. Halimede and Neso were discovered in 2002, and Psamathe a year later. Neso and Psamathe both orbit very far away from Neptune; Psamathe orbits at 48 million kilometres (30 million miles) away. Both of these moons may have come from a larger moon.

The six inner moons have regular, prograde orbits: Naiad, Thalassa, Despina, Galatea, Larissa and Proteus. Little is known about the four innermost moons, except that they are small and irregularly shaped. All of these likely formed from debris leftover when Triton was pulled into orbit. Naiad is the innermost moon and was discovered in 1989 by Voyager 2. It orbits just 23,500 kilometres (14,600 miles)

above Neptune. Thalassa was discovered around the same time. These two innermost moons orbit between two rings, Galle and Le Verrier. Despina, the third-closest moon, lies inside the Le Verrier ring, and the next moon, Galatea, may serve as a shepherd moon, holding the Adams ring in place.

Larissa, the fourth-largest moon, was discovered in 1981. It is known to be about 200 kilometres (124 miles) in diameter and with an elongated shape. It's also heavily cratered. Proteus, the outermost of these moons, is also the second-largest moon in orbit around Neptune. Voyager 2 also discovered it, and we learned then that it is at least 400 metres (248.5 miles) in diameter. Proteus is also heavily cratered.

Neptune's ring system was first spotted in 1984 in Chile, by a group of international astronomers. Astronomers prior to this had suspected rings when observing dips in the brightness of stars viewed between the observer and the planet. The existence of the rings was proven by images taken by Voyager 2, and we have since viewed the brightest rings using the Hubble Space Telescope as well as Earth-based telescopes. There are five distinct rings, named in order of their distance from Neptune: Galle, Le Verrier, Lassell, Arago and Adams. Galle is a very faint ring, named after the first astronomer to

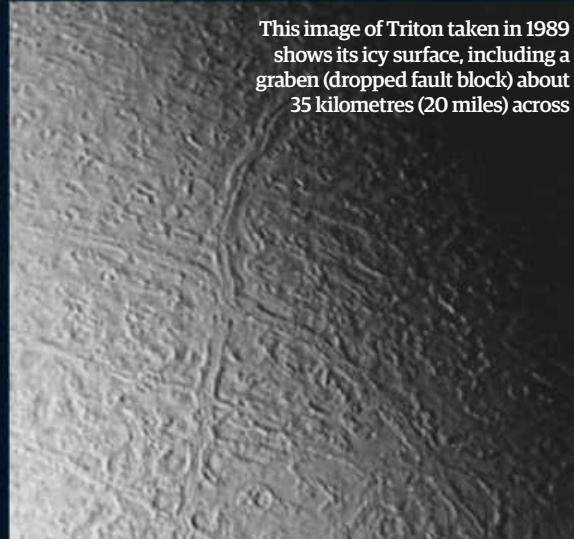
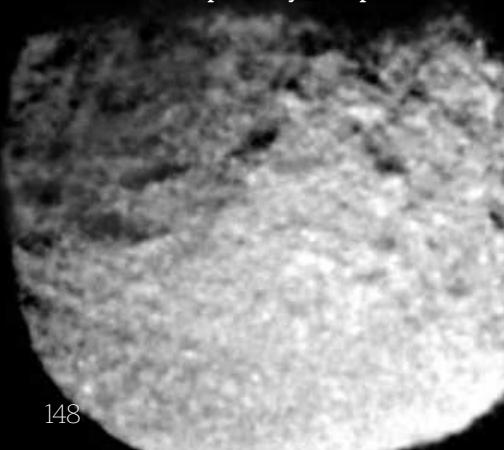
view the planet. The next ring, Le Verrier, is extremely narrow at just 113 kilometres (70 miles) wide. Le Verrier may be confined by the moon Despina, which orbits just inside it.

Neptune's widest ring, Lassell, is also called the plateau. It's a thin sheet of dust stretching from Le Verrier to the next ring, Arago. Some don't consider Arago to be a ring at all; it looks like a bright rim around the edge of Lassell, but is less than 100 kilometres (62 miles) wide.

We know the most about the outermost ring, Adams. It is a narrow ring slightly slanted. The moon Galatea shepherds the Adams ring and creates 'wiggles', or perturbations, at 42 different places in the ring. Adams has an unusual feature: five bright spots called arcs located along the ring, where the particles of dust are clustered together. They're named Fraternité, Égalité 1, Égalité 2, Liberté and Courage. Courage is the faintest, while Fraternité is the brightest. Ground-based telescopes first detected them, and Voyager 2 confirmed their existence. They have dimmed slightly since their discovery and some of the arcs seem to have moved slightly, but overall they are stable. We just aren't sure why the dust particles have clustered together in those areas. There could be as-yet-undiscovered moons or moonlets, or the arcs could be caused by an unusual resonance with the moon Galatea.

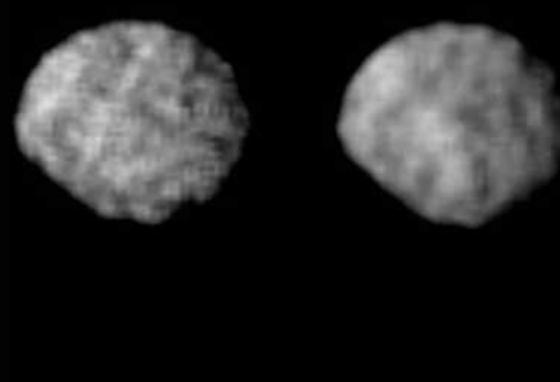
**"Triton comprises more than 99 per cent of the total mass in orbit around the planet"**

Although Proteus is the second-largest moon, it wasn't discovered until 1989 because of its dark surface and close proximity to the planet



This image of Triton taken in 1989 shows its icy surface, including a graben (dropped fault block) about 35 kilometres (20 miles) across

Voyager 2 took these two images of Larissa, the fifth-closest moon of Neptune. It is cratered and irregularly shaped



## Triton, Neptune's most amazing moon



## The rings of Neptune

### 1. Galle

Galle is 2,000km (1,240 mi) wide and orbits Neptune at a distance of 41,000 to 43,000km (25,500 to 26,700 mi).

### 2. Le Verrier

Le Verrier is 113km (70 mi) wide and orbits 53,200km (33,000 mi) away.

### 3. Lassell

Lassell is more like a broad dust sheet than a ring, with its orbit around Neptune between 53,200 and 57,200km (33,000 and 35,500 mi).

### 4. Arago

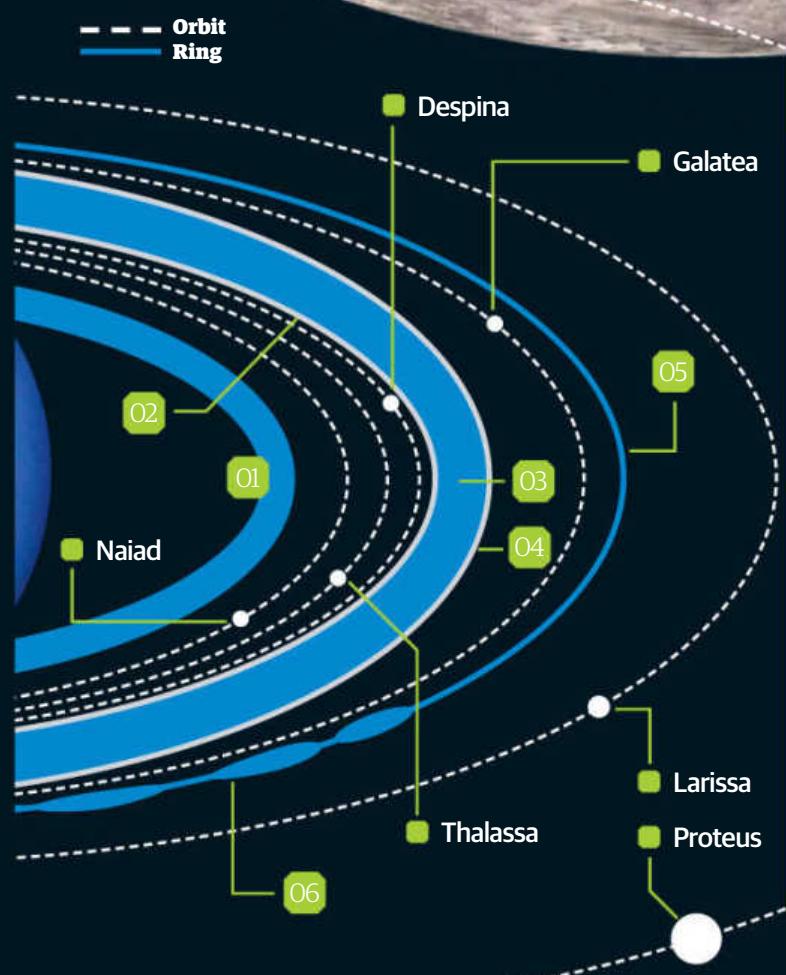
Arago orbits Neptune at 57,200km (35,500 mi) and is less than 100km (62 mi) wide.

### 5. Adams

Adams is 35km (22 mi) wide and orbits around Neptune at 62,900km (39,000 mi).

### 6. Arcs

These arcs are the particles of dust clustered together in the Adams ring, named Fraternité, Égalité 1, Égalité 2, Liberté and Courage.



## Neptune in numbers

Fascinating figures about the eighth planet from the Sun

# 500,000

A 1999 study at the University of California simulated the atmospheric pressure of Neptune and estimated it to be 100,000 to 500,000 times that of the Earth's

# 17% 248 years

Neptune's gravity is only 17% stronger than Earth's gravity - the closest of any planet in the Solar System

*Neptune will be closer in its orbit to Pluto than to the Sun for 248 years, as Pluto's eccentric orbit takes it inside Neptune's*

# 1/900

Neptune receives 1/900th of the energy from the Sun that the Earth receives

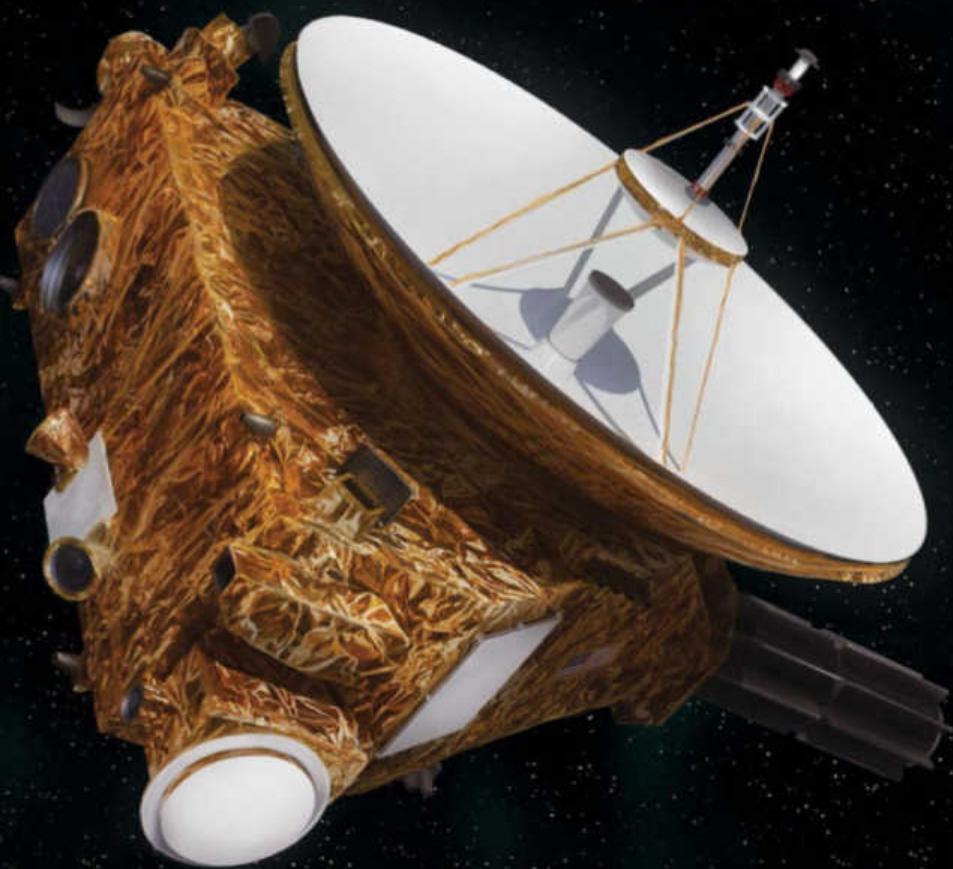
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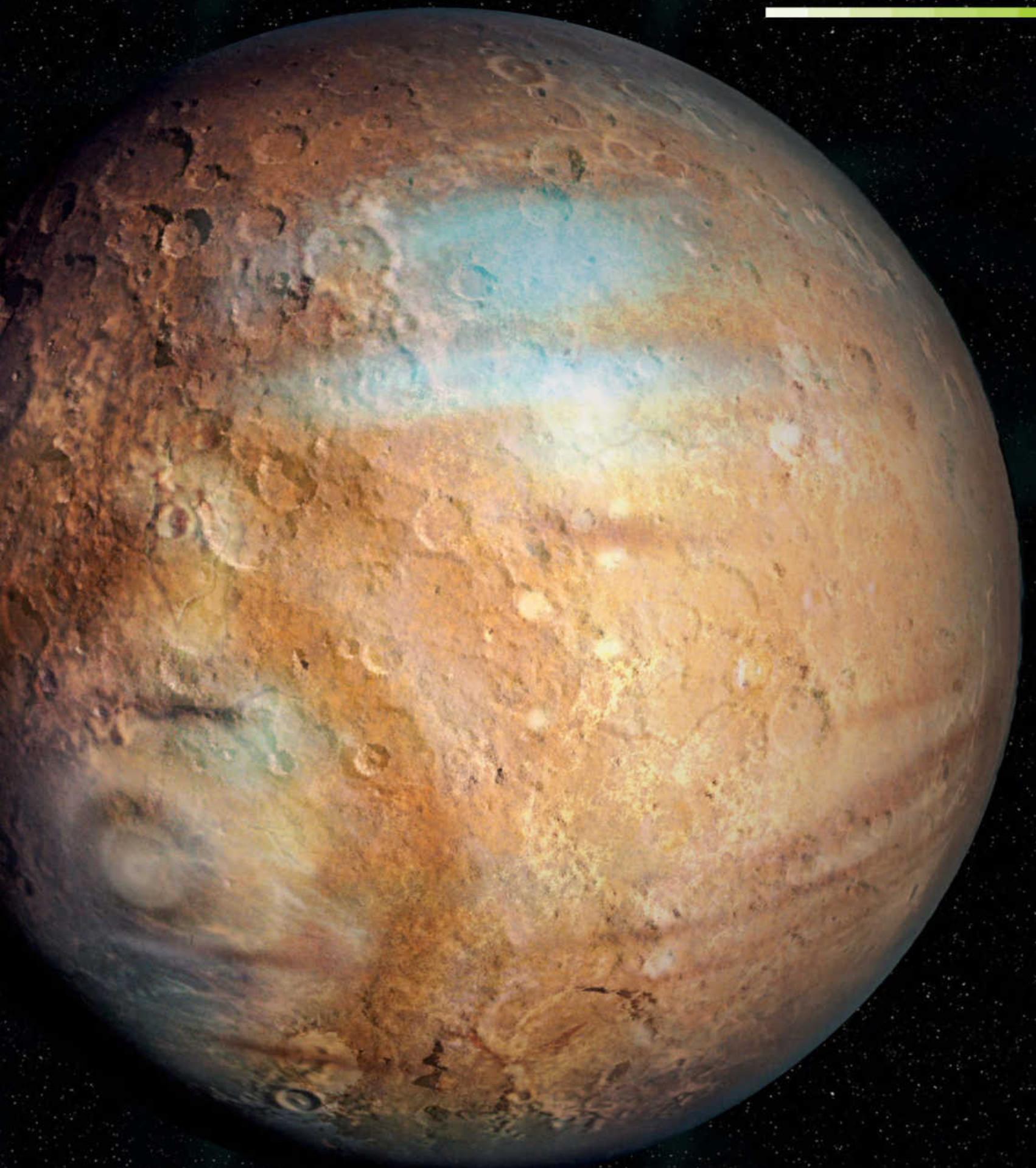
# 100 yrs

*Neptune's moons are named after Greek and Roman water deities, since the planet is named after the god of the sea. None of the moons were named immediately after discovery - in Triton's case, it took over 100 years*

# PLUTO OUR LAST FRONTIER

Pluto has long interested astronomers but it has never been explored by space probes... until now





It has been on a breathtaking journey 4.8 billion kilometres (3 billion miles) long. It has taken nine-and-a-half years. And it has cost \$700 million (£460 million). But for patient astronomers working on the New Horizons mission, the spacecraft which is about to make the first-ever reconnaissance of Pluto is more than worth its half-ton weight in gold.

Launched on 19 January 2006, New Horizons is set to spend this summer flying by Pluto and its five known moons. It is already the closest man-made object to Pluto, but very soon it will be within a space whisker and scientists are very excited about the possible discoveries it will enable them to make.

"Imagine the explorers of old who crossed the oceans," says Dr Alan Stern, the principal investigator of the New Horizons mission. "They will have had some of the same feelings we are having after their long journeys. I just tell people, if you are anything like me then you will fasten your seat belt because I expect that you will be in for one heck of a ride."

Pluto's history has already been on something of a rollercoaster. Hypothesised by US astronomer Percival Lowell in the early 1900s, it was finally discovered by Clyde W Tombaugh on 18 February 1930. A month later, this object believed to be the ninth planet was officially named, but it was stripped of its planetary status by astronomers in 2006.

**"I just tell people, if you are anything like me then you will fasten your seat belt because I expect that you will be in for one heck of a ride"**

**Dr Alan Stern, New Horizons principal investigator**

Today Pluto is classified as a 'dwarf planet' since its highly elliptical orbit overlaps with that of Neptune. But that matters little to Dr Stern and his team at the Southwest Research Institute, which was granted the mission by NASA following an open competition in 2001. For, regardless of its status, Dr Stern views New Horizons as a giant leap forward. "At one point we even considered naming the mission One Giant Leap," he reveals. And he firmly believes the wait will be worth it: "Space missions are usually over in less than nine years but ours is only just beginning."

To get ready for the mission, Dr Stern and his team had to work fast. As soon as they were chosen to head the mission, they knew they needed a Jupiter gravity assist if they were to get to Pluto within nine-and-a-half years. "But that meant getting this built and launched in four years and two months because the Jupiter gravity assist that we used to go to Pluto was the last one for a decade," he says. It represented a record: Cassini-Huygens, which was sent to Saturn, took a decade to be built, as did Galileo, which studied Jupiter. In order to achieve it, the team worked nights and weekends for four years straight.

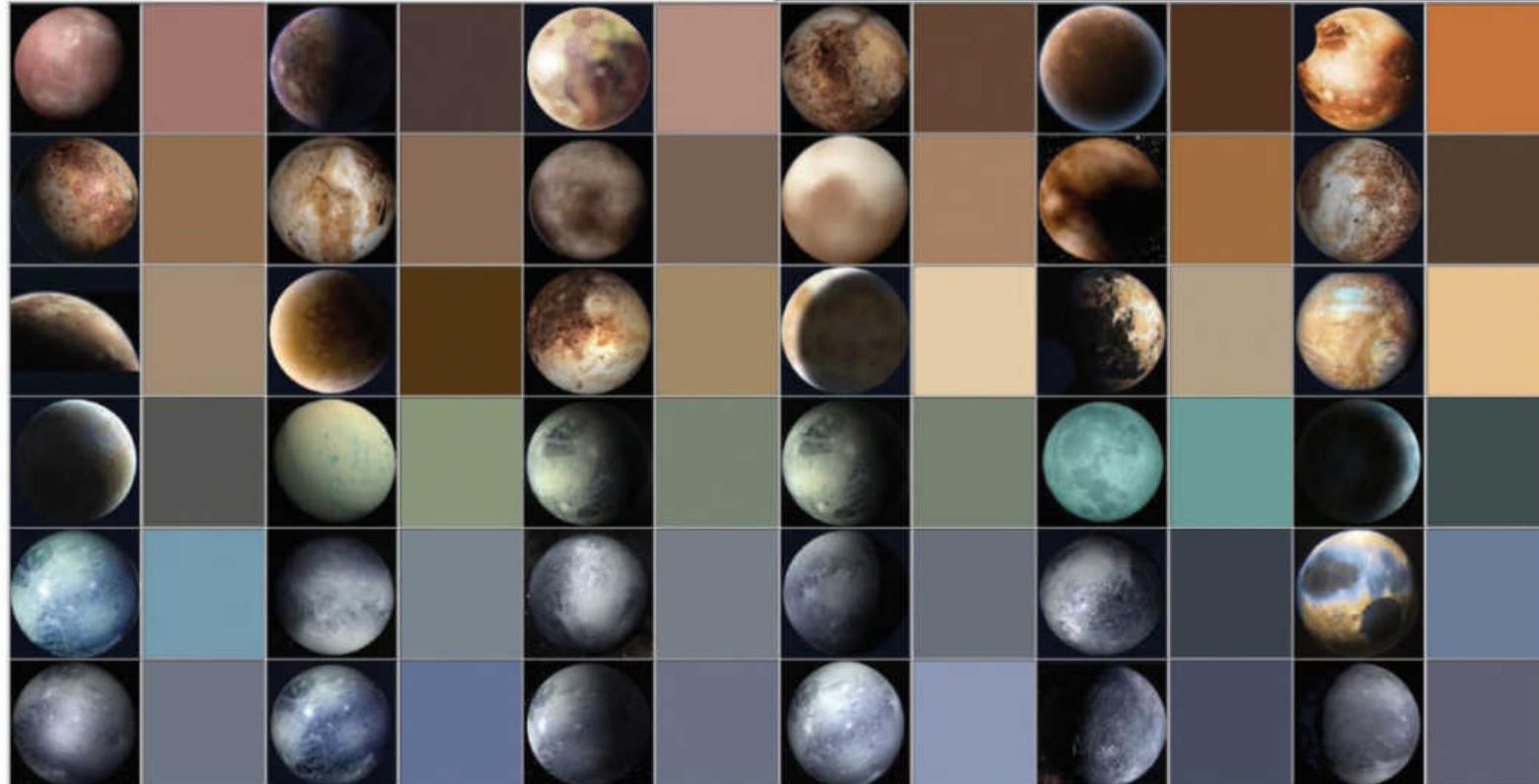
The results have been impressive, though. Five times less expensive than Voyager, New Horizons has not relied on the invention of new spacecraft technology but it has a good set of seven instruments

on board. "We put all of our technology into better cameras, better spectrometers, more capability to return data," says Dr Stern. In February 2007 as New Horizons swung past Jupiter for a gravity boost, the team was able to test the spacecraft systems and instruments on a practice flyby. More than 100 scientific papers using data from the Jupiter flyby were published and it also made the cover of *Science* magazine. When asked what he expects to find on Pluto, though, Dr Stern laughs: "If I knew, I wouldn't have to do the mission."

New Horizons came out of hibernation for the last time on 6 December 2014 as it made its final



Created by astrophysicist Alex Parker using 60 unique images to represent Pluto from the internet, the chart below estimates typical colours for the dwarf planet



## Passengers to Pluto

NASA has sent slices of humanity – as well as Pluto's discoverer – into space



### Photos

A CD-ROM containing images of the people who have worked on New Horizons has been added to give the mission a personal touch.



### Commemorative coin

A Florida state quarter – a commemorative coin released by the United States Mint between 1999 and 2008 – pays homage to the spacecraft's Cape Canaveral Air Force Station launch site.

### Maryland Quarter

New Horizons was built in the US state of Maryland and so a commemorative quarter with a design depicting the area on its reverse has also been included.



### People's names

Mounted on the exterior of the New Horizons spacecraft is a CD-ROM containing 434,738 names, maintaining a long-standing tradition to fly a full list of active Planetary Society members into space.



### Founder's ashes

Clyde Tombaugh, who discovered Pluto, is going along for the ride – or at least a portion of his ashes are. They are stored underneath the spacecraft in a container.



### SpaceShipOne

On the lower inside deck of New Horizons is a small piece cut from SpaceShipOne, a suborbital air-launched spaceplane that completed the first manned private spaceflight in 2004.



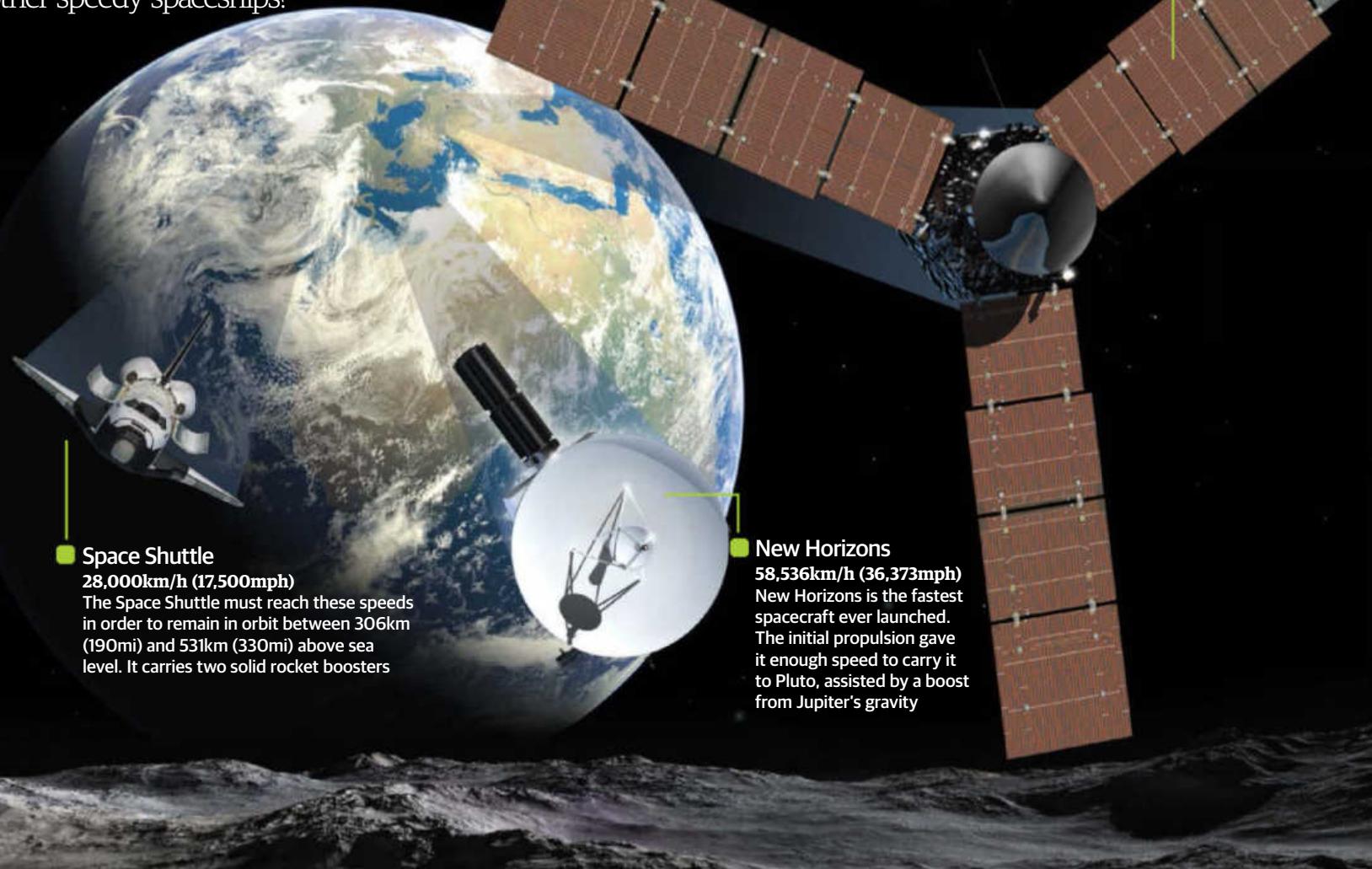
### Collectible stamp

NASA has been recognised by America's Citizen's Stamp Advisory Committee on more than 36 stamps since 1967. One, in 1991, carried the words 'Pluto: Not Yet Explored', and is on board New Horizons.

# Fastest missions

How does New Horizons compare to other speedy spaceships?

**Juno**  
257,500km/h (160,000mph)  
Juno's mission to Jupiter passed around Earth, giving it an acceleration boost akin to the propulsion of a second rocket launch. On arrival at Jupiter in 2016, gravity will increase speeds further



approach. Since then it has observed Pluto for an entire 6.4 Earth-day rotation, watching it wobble slightly thanks to the gravity of its largest moon, Charon. It has also revealed a large bright area at the pole of Pluto. The science team cannot know for certain what it is until the composition is tested but it suggests the presence of a polar cap. With broad dark and bright regions across the icy world, even at a distance of 113 million kilometres (70 million miles), it was viewed as a major discovery.

"Pluto showed dramatic markings, telling us that it is a special place; that is different from most of the others especially because only the Earth has had anything similar," says Dr Stern. When the spacecraft gets closer, things will become even clearer. That's when discoveries will be made at a rate of knots with astronomers keen to find out if there are other possible moons and even whether there are rings around Pluto.

"If we did see rings then what we could conclude would depend on what we found, the number and locations and densities of them, but it would be exciting," says Dr Stern. "The possibilities are many." Indeed, there are many mysteries waiting to be found and explained: the surface composition is said to include nitrogen, carbon monoxide, methane and

water ices, for instance, but many other materials may be present and undiscovered.

There is even a possibility, no matter how small, of life. Pluto is two-thirds rock and one-third water in the form of water ice. It has more than three times as much water as all of the Earth's oceans. If either have an ocean, meaning the water would be warm enough to be liquid, there could theoretically be life on Pluto or Charon. If that was the case they would, like Saturn's moon Enceladus and Jupiter's moon Europa, go on the list of potential astrobiological targets.

What is just as fascinating is that, during the five months it will spend observing Pluto close-up, the dwarf planet will barely have moved. Pluto only orbits the Sun once every 248 Earth years but it's not the only focus of New Horizons' mission. Its secondary objective is to make the first exploration of the small bodies in the disc-shaped Kuiper belt region, which Dr Stern says "turns out to be the largest class of planet in the Solar System."

The Kuiper belt contains bodies of mainly ice and rock. But there are potentially trillions of Kuiper belt objects, hundreds of thousands of them believed to be larger than 100 kilometres (62 miles) in size, plus many, many more as small as one kilometre (0.62 miles). Eris is one of the icy worlds and several of

the dwarf planets have tiny moons. "There are more known Kuiper belt planets than there are gas giants and terrestrial planets combined," says Dr Stern. "So this is a very important new and unexplored class of targets in the Solar System."

Pluto remains the primary focus, though. As New Horizons approaches, the spacecraft's dust and charged particle instruments have been taking measurements. Operating every day and sending home data every week, they have been telling scientists about Pluto's wider environment. When scientists get close-up data, they will be able to interpret it in context.

"It has confirmed models of the expected dust density but that was no surprise," says Dr Stern. "It has amplified on the kind of information that the Voyager spacecraft obtained when it went through the Kuiper belt. The instrumentation that we are carrying to study the solar wind and other charged particles is vastly more sensitive, so we can see many more details. Even this far from the Sun, the spacecraft is crossing interplanetary shocks, supersonic shocks in the solar wind, which Pluto also crosses - and so do the other Kuiper belt objects. So we are just characterising the space weather environment out there."

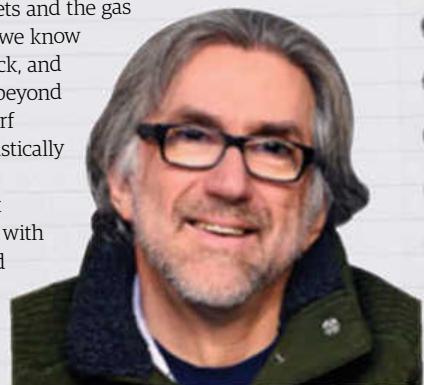
# Is Pluto still a planet?

Leading experts give their views on the controversial decision to downgrade Pluto to a dwarf planet in 2006

## YES

**Dr William B McKinnon**, professor at the Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St Louis

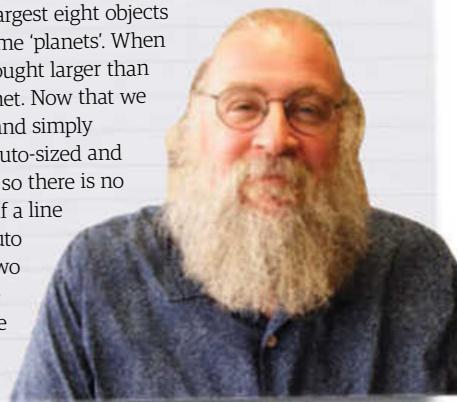
"Pluto is a planet. But it is a small, or dwarf, planet. It is the exemplar of an entirely new class of planets, the other classes being the rocky terrestrial planets and the gas giants. All of the dwarf planets we know of so far are made of ice and rock, and most reside in the Kuiper belt, beyond Neptune. But the idea that dwarf planets are not planets is linguistically sloppy and a bit silly. Planetary scientists study bodies, not just masses and orbits, and a world with five moons, an atmosphere and hints of a complex history, is a planet enough for most of us."



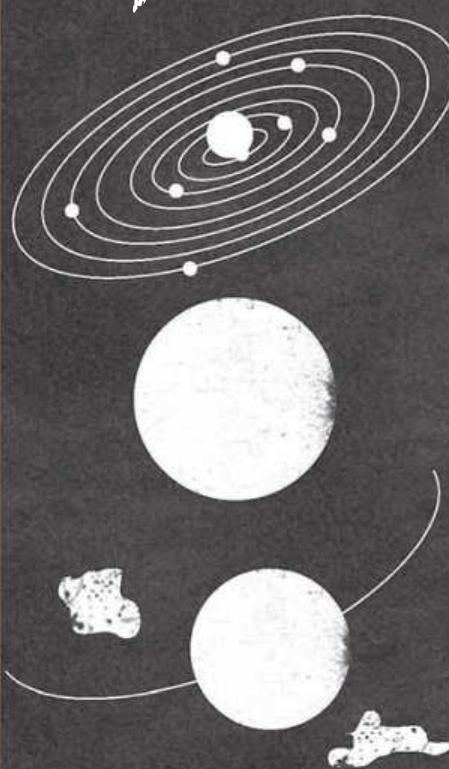
## NO

**Dr Hal Levison**, planetary scientist specialising in planetary dynamics at the Space Studies Department of the Southwest Research Institute

"Scientists typically classify objects into groups based on natural boundaries. [When looking at] the size and orbits of objects in the Solar System, it's clear the largest eight objects stand apart and deserve the name 'planets'. When Pluto was discovered, it was thought larger than Earth and isolated, hence a planet. Now that we understand that Pluto is small and simply part of the Kuiper belt. Many Pluto-sized and smaller objects exist there, and so there is no natural dividing line between. If a line is artificially drawn to make Pluto a planet, there will always be two objects of almost the same size and appearance, but one will be a planet and the other won't."



## Definition of a planet



### It has to orbit the Sun

The Sun is the centre of the Solar System and it pulls planets into a curved orbit. The International Astronomical Union says this is a fundamental definition for a planet.

### It must be round (ish)

If the celestial body has sufficient mass so that its own gravity squashes it into a ball that is as round as possible, it assumes a - planetary - hydrostatic equilibrium.

### It needs its own space

That is, it must "clear the neighbourhood around its orbit". It means the body has become gravitationally dominant with no other comparably sized bodies in its vicinity.

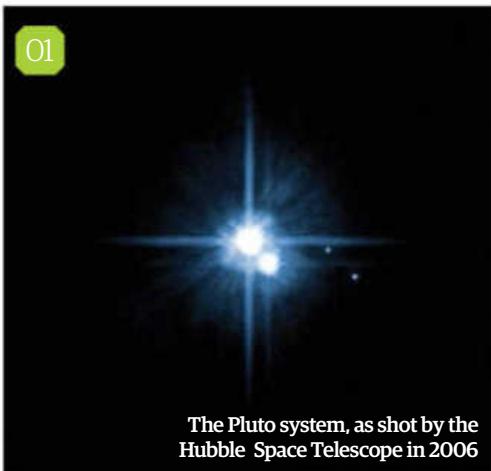
It will also be a good opportunity to find out more about the aspects of Pluto astronomers are certain about. It is understood Pluto has low surface gravity, an estimated temperature of -233 degrees Celsius (-387 degrees Fahrenheit) and its atmospheric pressure is 100,000 times less than Earth's. "We know for a fact that Pluto's surface markings have moved and changed since the Nineties and we know for a fact that Pluto's atmospheric pressure has more than doubled since the Eighties, so we know that Pluto is dynamic; it's changing," says Dr Stern.

But Pluto's moons represent more of an unknown. When New Horizons was being planned, Charon was Pluto's only known moon. But, months before the mission launched, the Hubble Space Telescope (HST) suggested Pluto had two extra moons: Nix and Hydra. There were more to come too. In July 2011, HST found a fourth moon and, a year later, a fifth. They were called Kerberos and Styx.

"There is still circumstantial evidence that there could be surface activity on the big moon, Charon. We see that because we have detected crystal and water ice there - and crystal and ice can't survive for a very long period in space," says Dr Stern. "The radiation in space changes the crystal structure so the fact that we see hexagonal crystals tells us that ice must be young. We also see, compositionally, a material on the surface of Charon called ammonia hydrate, which often is the result of cryovolcanism, a cold form of volcanism. Those are two hints that Charon may be active."

The discovery of the extra four moons changed the mission in two significant ways. Not only was the team able to schedule observations of them into the mission - "if we hadn't known about them we couldn't have done that" - they had to rethink the logistics of the flyby. "We realised these four satellites could present hazards, not because we are going to hit one but when there are craters, the shrapnel that comes out of the hole can get into orbit around Pluto and be a danger," says Dr Stern. "So we put in place a seven-week search for hazards that New Horizons initiated in May, lasting all the way down until we are almost at Pluto. It will be searching to find out if the path that we plan to fly is safe or not. If it is not then we will fire the engines and move the spacecraft trajectory to a safer place."

A 93-second thruster burst has already adjusted the trajectory of New Horizons. It slowed the velocity



The Pluto system, as shot by the Hubble Space Telescope in 2006

## Pluto: the missing pieces

There are many things we don't know about Pluto. We asked leading scientists what they hoped to learn



### 01 How Pluto fits in

**Dr Harold Weaver, New Horizons project scientist, The Johns Hopkins University Applied Physics Laboratory**

"I want to transform Pluto from a pixelated blob into a world with complexity and diversity. What does Pluto's landscape really look like? Are there high mountains and deep valleys? Are there cryovolcanic vents hinting at interior activity? And how do Pluto and its moons compare to other bodies in the Solar System?"



### 02 Pluto's actual size

**Dr Marc Buie, astronomer, Southwest Research Institute**

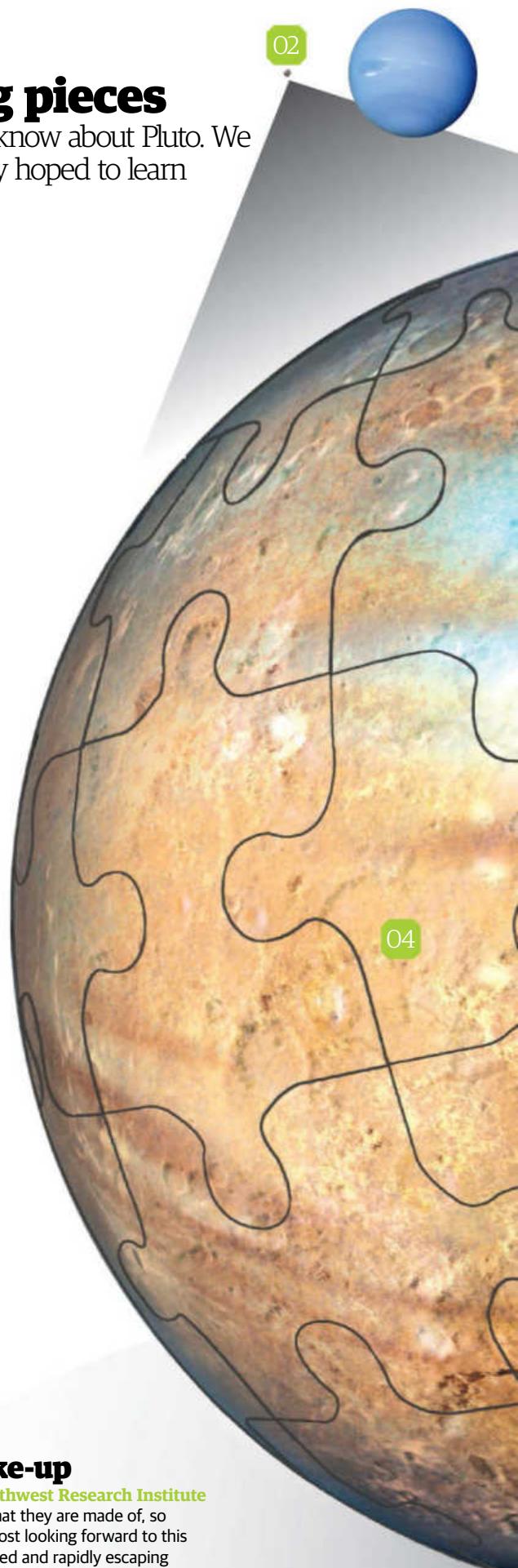
"The simplest thing I want to learn is the actual size of Pluto. However, I also really want to see how geologic and surface processes on Pluto relate to the known albedo patterns. Are they connected or are they independent?"



### 03 The atmospheric make-up

**Dr Randy Gladstone, institute scientist, Southwest Research Institute**

"I'm interested in how atmospheres work and what they are made of, so learning that (at long last) for Pluto is what I'm most looking forward to this summer. Pluto's atmosphere is likely very extended and rapidly escaping (because Pluto is small), with a lot of the same molecules found in Titan's atmosphere, but I still expect to be surprised."





### The surface composition 04

**Dr Cathy Olkin, principal scientist, Department of Space Studies at the Southwest Research Institute**

"I am interested in what the surface of Pluto is made of.

I have spent years studying Pluto through telescopes looking at the signatures of surface materials (mostly ices of different types: methane, nitrogen and carbon monoxide) on Pluto's surface. The close-up investigation of Pluto by New Horizons will allow us to map the surface composition of Pluto and that is something that I am very excited about."



### The solar wind interaction 05

**Prof Fran Bagenal, professor of astrophysical and planetary sciences at the University of Colorado, Boulder**

"How does Pluto's escaping atmosphere interact with the atmosphere escaping from the Sun - the solar wind? We expect to measure where the ionised component of Pluto's atmosphere holds off the solar wind and this will tell us how much material is escaping. Current estimates are about 1,000 truckloads a day!"



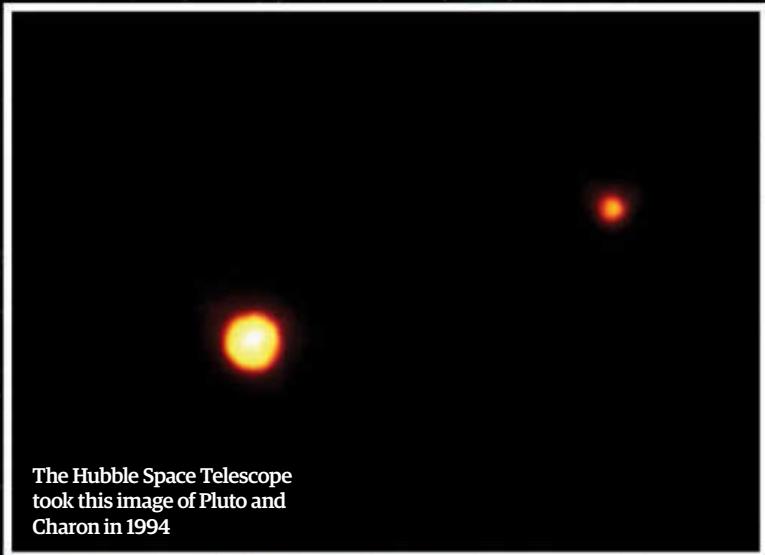
### The geologic processes 06

**Dr Jeffrey Moore, scientist, NASA Ames Research Center**

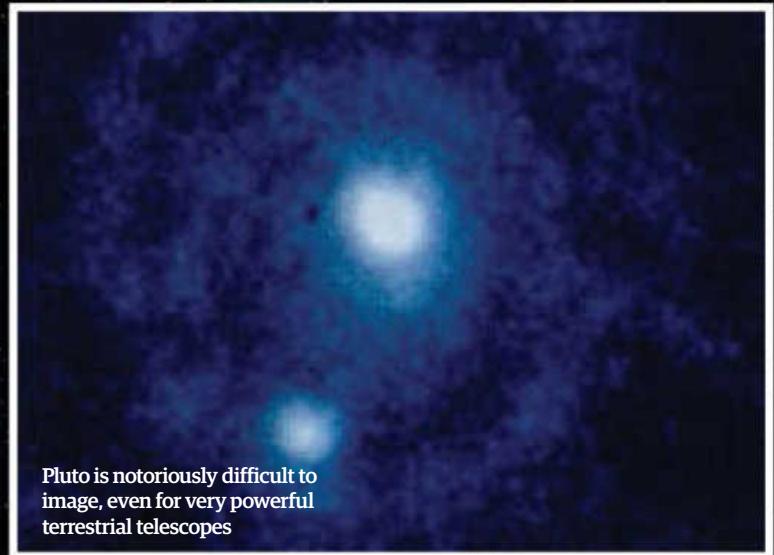
"I'm a geologist so I want to know what are the geologic processes that have shaped the surface of Pluto and its moon. It is important to understand which processes came first, and which ones are still acting on its surface. Maybe we'll see evidence for internal activity. Hopefully we can decipher the geological histories of Pluto and its moon."

## Imaging a distant, cold dwarf planet

From clear shots of its moons to a possible polar cap, Pluto is revealing itself bit by bit



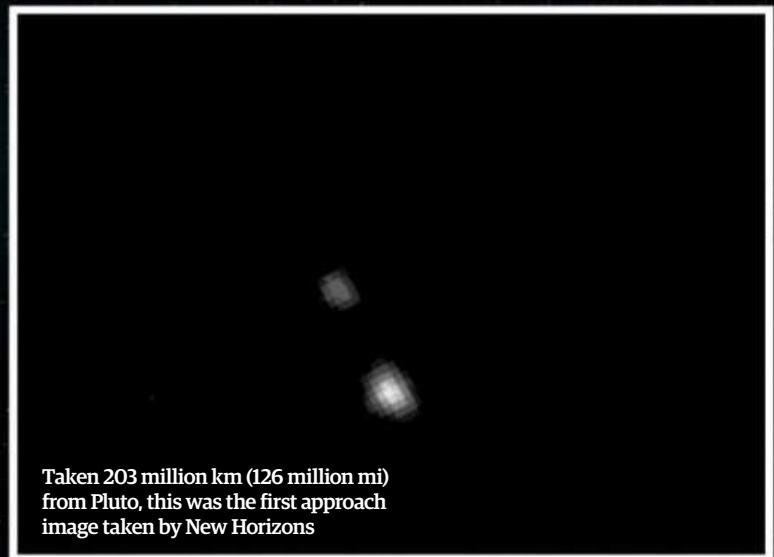
The Hubble Space Telescope took this image of Pluto and Charon in 1994



Pluto is notoriously difficult to image, even for very powerful terrestrial telescopes



The Pluto-Charon System, taken by the European Southern Observatory's Very Large Telescope



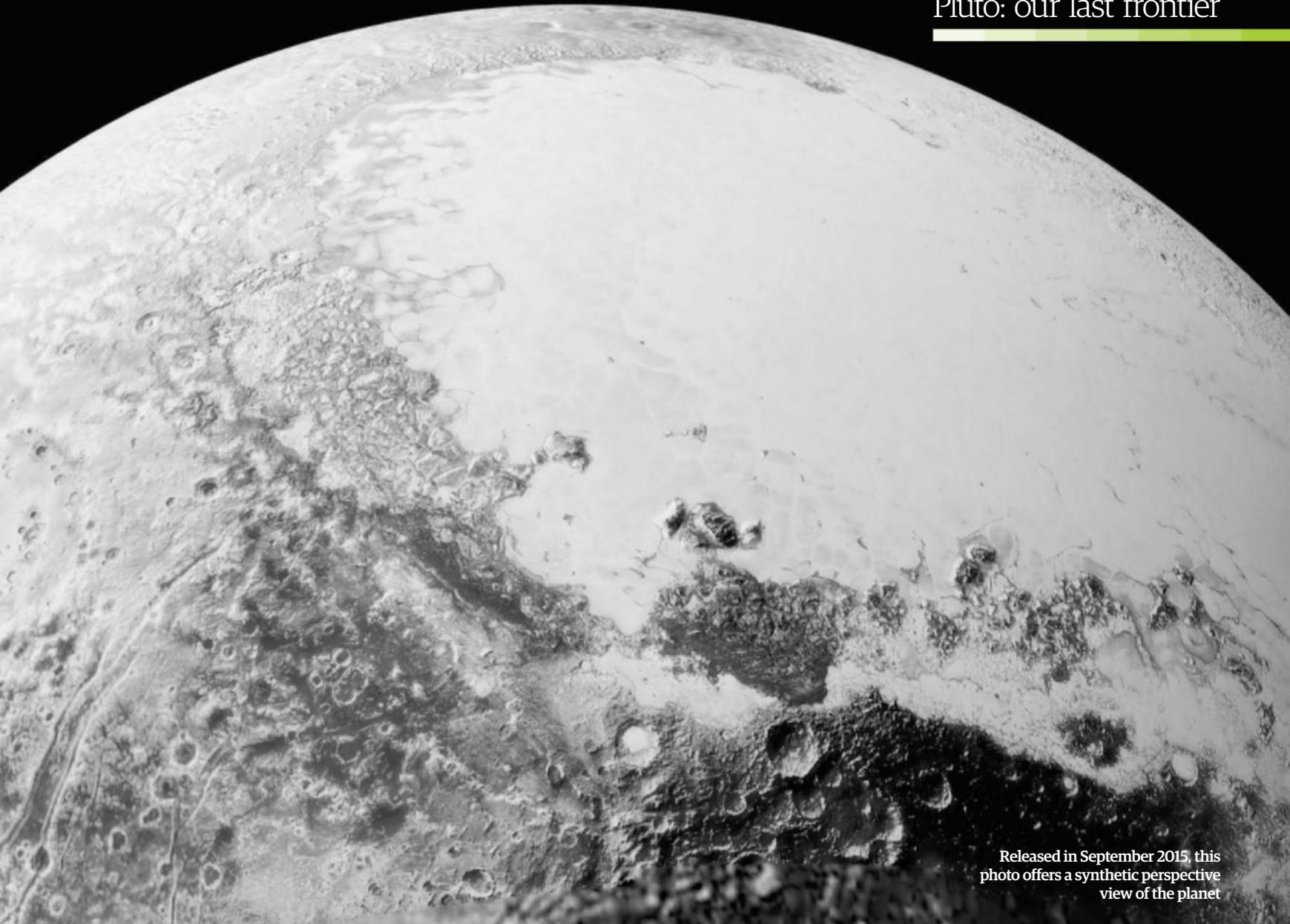
Taken 203 million km (126 million mi) from Pluto, this was the first approach image taken by New Horizons



Pluto and its largest moon, Charon, on 9 April - captured in colour for the first time by New Horizons



Bright and dark regions can be seen on Pluto, with astronomers detecting a possible polar cap



Released in September 2015, this photo offers a synthetic perspective view of the planet

of the spacecraft by 1.14 metres (3.7 feet) per second on 10 March and this shifted the course sideways by 3,442 kilometres (2,139 miles), pushing it towards the desired close-approach point of Pluto. But the moons continue to fascinate. On 18 February this year, New Horizons' Long-Range Reconnaissance Imager (LORRI) provided its first long-exposure views of Nix and Hydra at distances ranging from 201 million to 185 million kilometres (125 million to 115 million miles). By 13 May, it had brought Kerberos and Styx into view. Together with Charon, which had already been seen due to its size and greater brightness, it has meant all five moons have now been detected.

When the spacecraft gets close to the moons, it will seek to map their surfaces at a specified resolution and map their surface composition at another resolution. It will do the same when it nears Pluto itself. "We will map the surface geologies, the surface temperatures," says Dr Stern. "We'll map the composition, which means we will obtain spectra at

literally hundreds of thousands of locations on the disc. We will map the surface topography because we will do stereo imaging so there are a whole variety of different maps that we will make.

"By combining them - looking at the geology, the composition of the different types of features or whether there are thermal hotspots, for example - it can inform us what is going on in the planet, what's going on on the surface. It will tell us how Pluto has evolved and how it originally came to be."

At the same time, Dr Stern insists the spacecraft is not there to answer questions even though many can be posed. "We don't know what questions to ask," Dr Stern explains. "We are there to collect certain data sets that will allow us to explore the Pluto system. It's what the early space programme was about but done with 21st century technology."

More than 1,000 images are being sent to the ground team on its way to the encounter and while LORRI may be the least sophisticated instrument on

the spacecraft, it will arguably produce some of the most exciting data. "It's got a big telescope in front of it so it's high magnification," says Dr Stern. "But it only has one charge-coupled device (CCD) and it's black and white, what we call panchromatic."

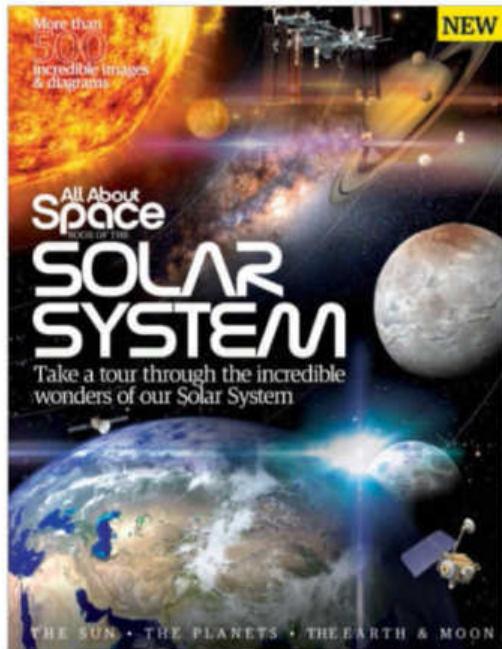
Those high-resolution images will be backed up by snaps taken from a digital imager called Ralph. Ralph will make the maps that show what Pluto, Charon and the Kuiper belt objects look like at light levels 1,000 times fainter than daylight at Earth. On 14 April this year, it took the first colour image. Eventually it will deliver images showing surface features as small as a few miles across. "It has eight CCDs, both colour and black and white, both scanning and framing cameras, and inside it also has an infrared mapping spectrometer with 64,000 pixels that is dramatically advanced compared to the Voyager devices of the same type," Dr Stern explains.

This will help to ensure that space enthusiasts and astronomers are glued to their TVs and the internet as more images and news filters through. "This

mission is the capstone to the historic first era of reconnaissance, the equivalent of the summing up of Mount Everest," says Dr Stern. "It is just as significant as when the last of the continents of Earth were conquered... I can't be more proud of the team."

**"We'll map the composition and obtain spectra at hundreds of thousands of locations on the disc"** **Dr Alan Stern**

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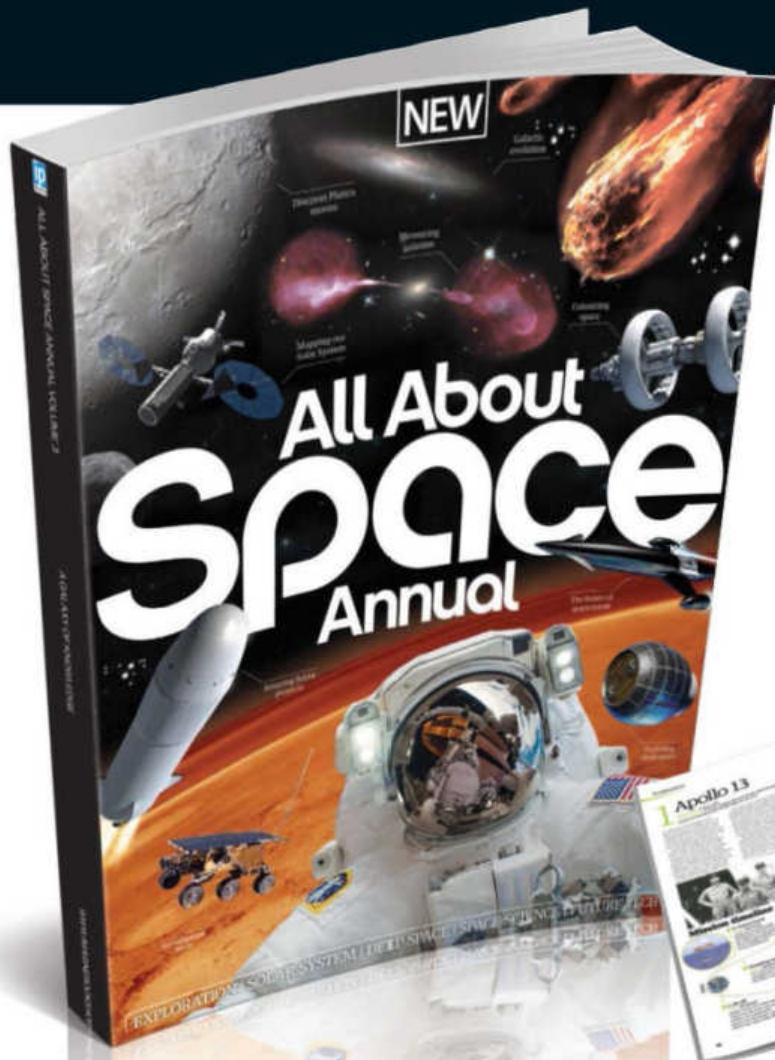
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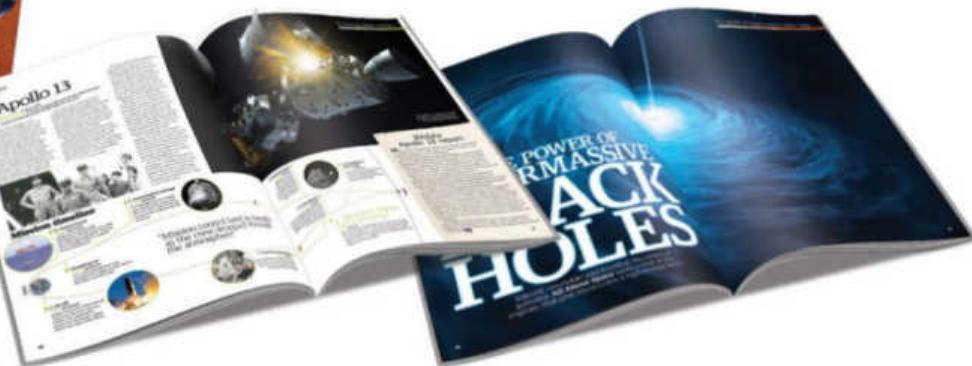
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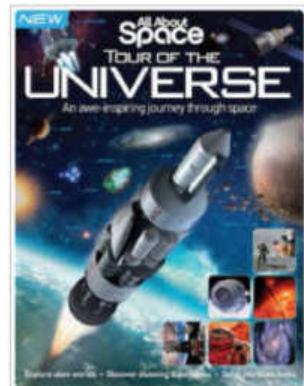
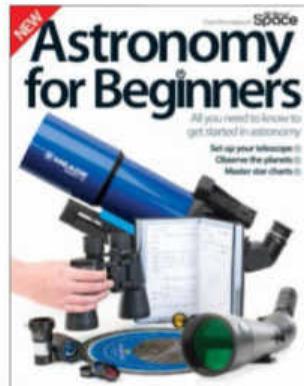
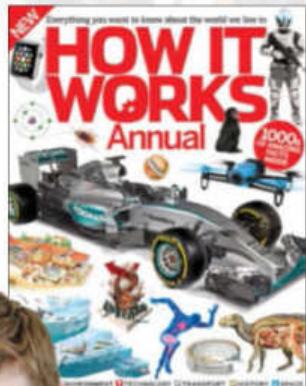
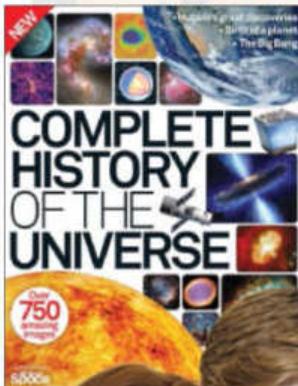


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